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Bridge frost prediction by heat and mass transfer methods

Tina Marie Greenfield
Iowa State University

Bridge frost prediction by heat and mass transfer methods

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Tina Marie Greenfield

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Program of Study Committee:
Eugene S. Takle, Major Professor
William A. Gallus, Jr.
Brian K. Hornbuckle

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Tina Marie Greenfield

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Contents

List of Tables

List of Figures

Chapter 1. Introduction

Frost frequently forms on roads and bridges during Iowa winters when the pavement temperature is at or below 273 K and below the dew-point temperature. Takle (1990) concluded that there are about 20 roadway frost events and 12 to 58 bridge frost events in Iowa each year. Frost on roadways and bridges can present hazardous conditions to motorists, especially when it occurs in patches or on bridges when adjacent roadways are clear of frost. The Iowa Department of Transportation chemically treats roadways and bridges to prevent frost formation to maintain safe driving conditions during the frost season. To minimize negative environmental impacts, vehicle corrosion, and materials cost, frost-suppression chemicals should be applied only when, where, and in amounts needed to maintain roadways in a safe condition for motorists. Accurate forecasts of frost onset times, frost intensity, and frost disappearance are needed to help roadway maintenance personnel decide when, where, and how much frost-suppression chemicals should be used.

Accurate frost forecasts rely on accurate forecasts of bridge surface temperature and ambient atmospheric conditions (i.e., air temperature, humidity, precipitation, and wind speed). All these factors except bridge surface temperature are routinely calculated by weather forecast models such as the Pennsylvania State University/ National Center For Atmospheric Research (PSU/NCAR) mesoscale model (MM5) or the NCAR Road Weather Forecast System (RWFS) (Mahoney and Myers 2003). Although numerical weather models do not forecast bridge temperature, many models calculate the ambient parameters needed to derive the temperature of a bridge that is being influenced by the predicted weather.

A finite-difference program (BridgeT) has been developed that predicts bridge surface temperature by simulating vertical heat transfer in a bridge in response to evolving weather conditions produced by a forecast model. A vapor flux calculation within BridgeT uses the bridge surface temperature and concurrent meteorological variables from the forecast model to produce forecasts of incremental volume per unit area (i.e., depth) of frost deposited, melted, or sublimated.

A physically based method was chosen for this bridge condition model because the necessary information to derive the heat and vapor fluxes to the bridge is already available through mesoscale forecasting models. Statistically based methods require large amounts of accurate observations for model training which may not be available for certain sites. Additionally, frost and observations of other bridge conditions may not be regularly or reliably collected due to the effects of chemical treatment, irregular observing schedules and locations, or inaccurate observation practice. Physically based models do not need lengthy training data and may be better at forecasting bridge condition during periods of abrupt weather changes that are not predictable by analyzing local observations.

1.1 Objective

The focus of this research was to improve model-driven frost forecasts by creating an algorithm that allows a standard meteorological forecast model to more accurately predict bridge surface temperature. Previous research has shown that bridge surface temperature is required for calculations of vapor fluxes and bridge deck condition (wet, icy, frosty, dry). It is intended that BridgeT be accurate, adaptable, and easy to use in operational forecasting. BridgeT is not intended to replace human forecasters or other bridge condition models, but to be an additional resource for forecasters to make predictions about bridge conditions. BridgeT is similar but not identical to other models described in the following chapter.

Chapter 2. Previous research

2.1 Frost accumulation algorithm

A frost accumulation algorithm has been developed by Knollhoff et al. (2003) that uses Roadway Weather Information System (RWIS) observations or forecasts of air temperature, dew-point temperature, wind, and surface temperature to calculate frost accumulation through simple computations of moisture fluxes. Previous studies have shown that RWIS observations and unaltered MM5 forecasts used as input to this frost accumulation algorithm have been able to produce reasonably good calculations of frost occurrence when compared to up-close bridge frost observations (Greenfield et al. 2003). Table 2.1 shows the skill of 24-hour MM5-frost algorithm forecasts and RWIS-frost algorithm calculations for two frost seasons. Conventional measures of forecast skill for binary events include false alarm rate (FAR), probability of detection (POD), miss rate (MISS), probability of correct rejection (CR), and threat score (TS) (see Appendix 1).

Differences between frost occurrence calculated from RWIS observations and frost occurrence

Table 2.1 Skill of the Knollhoff frost algorithm using input from 24-hour forecasts (MM5) during one frost season and from two frost seasons of RWIS observations (RWIS).

Input used	FAR	POD	MISS	CR	TS
MM5 2001-02	0.52	0.9	0.09	0.31	0.45
RWIS 2001-02	0.57	0.57	0.43	0.78	0.4
RWIS 2002-03	0.2	0.8	0.2	0.97	0.67

reported by human observers (in Greenfield et al. 2003) can be explained by errors in observation or by differences in atmospheric conditions near the RWIS station and the bridges observed for frost occurrence. The distances from the RWIS site to the nearest and furthest observed bridges are approximately five and eight miles, respectively. Observations of air temperature, wind speed, and dew point temperature taken during the winter of 2001-02 from the RWIS site, the ASOS site near the Ames Municipal Airport, and a portable weather station located near State Avenue frequently showed discrepancies in observed values. Air temperature measurements were fairly consistent (to 1 K); however, the average differences among dew-point temperatures for the three stations were 3 to 6 K (Takle and Greenfield 2002). Assuming these differences are real and not due to instrument error, spatial differences in frost occurrence may be possible due to microscale weather differences at the different bridge locations.

The MM5-frost algorithm forecasts show skill in frost occurrence, but frost onset and disappearance times were unrealistic due to the fact that the surface temperature calculated by MM5 is the vegetation/ground surface temperature and is not representative of a bridge surface.

2.2 Roadway and bridge condition models

Several roadway and bridge temperature prediction models have been developed in recent years to fulfill the need for accurate road or bridge temperature forecasts. Bridge and roadway temperature models can use similar methods to determine heat fluxes through the road or bridge and atmosphere, whether based on energy balances or non-physical methods. However, roadway and bridge temperature distributions are not the same because bridges are constructed differently from roads. Bridges experience convective heat exchange from both top and bottom, and bridges have less thermal resistance due to their finite thickness. Some recent bridge and roadway models are described in the following paragraphs.

The Roadway Conditions Model described by Sass (1992) forecasts roadway temperature and conditions based on energy balance equations. Coupled to a good forecast model, it can produce quality road temperature forecasts out to at least 3 hours. An updated version (Sass 1997) produces 5-hour forecasts of roadway conditions and temperature for 200 road sites and is run operationally at the Danish Meteorological Institute. The average error of a 5-hour forecast is near 1 K using the High Resolution Limited Area Model for input. This model does not allow the formation of dew or frost.

The German Weather Service (DWD) Version 3 model (Jacobs and Raatz 1996) forecasts road conditions and road surface temperatures over a time period of 27 hours. It uses energy balance formulations forced by a model and supplemented by human forecasters. DWD model forecasts are calculated for 5 types of road surfaces, including bridges. The root mean square error (RMSE) of 24-hour roadway temperature forecasts using observational input is approximately 2.75 K overall, but improves during all clear or entirely overcast days. The RMSE for bridges was 2.8 K.

Shao and Lister (1996) developed Icebreak, a fully-automated now-casting model that is capable of producing 3-hour forecasts of road temperature and surface condition by projecting previous sensor observations to drive a physically-based surface energy budget. Test results show that this model successfully predicts 92% of frost and no-frost nights. The overall temperature RMSE is 1.6 K.

The HS4Cast model has been in operational use forecasting conditions along Austrian motorways. It is a statistical model that uses "fuzzy logic" and pattern analysis rather than energy balances to predict road surface temperatures out to 24 hours (Hertl and Sheffar 1998). It incorporates past events and effects of local terrain into site forecasts. The authors concluded that the HS4Cast forecast quality is similar to the forecasting centers of that time for the first six hours of the forecast. The HS4Cast is capable of running with very little forecaster intervention.

The Model of the Environment and Temperature of Roads (METRo) is a numerical model to forecast road and bridge conditions (Crevier and Delage 2001). METRo is the heat balance model that is the most similar to BridgeT. It is composed of modules for surface energy balances, heat conduction within the bridge, and effects of water and snow accumulation on the road. It uses input from Roadway Weather Information System (RWIS) stations for temperature initializations, is forced by a forecasting model (GEM), and accepts optional human forecaster modification. METRo uses a coupling phase–a feature that allows the model to adjust to the local differences between observation and forecast during the first hours of the run. Using the GEM, it outputs 24-hour forecasts twice a day. Twenty-four hour forecasts for the bridge site were verified every 20 minutes for 65 days during early spring. About one-half of the forecast values lie within 2 K. The RMSE tended to be larger during the daytime than at night. The minimum surface temperature RMSE for the bridge site was 1.76 K and the mean bias was 0.03 K.

Temeyer (2003) developed a series of models using an artificial neural network to forecast parameters important for frost formation. The network learned from observations from past years and predicted future weather based on pattern analysis. Temeyer concluded that this method produced accurate forecasts in the short-term, but developed cold biases in air and bridge temperatures as forecast time increased.

Chapter 3. BridgeT description

A one-dimensional, explicit, forward-difference algorithm (BridgeT) has been developed in a format similar to that used by Crevier and Delage (2001), that predicts bridge surface temperature by simulating vertical heat movement in a bridge in response to evolving conditions produced by a weather forecast model. Vapor fluxes toward and away from the bridge are calculated using bridge surface temperature and model-calculated precipitation rate, specific humidity, wind speed, and air temperature. Like METRo, BridgeT calculates heat fluxes due to natural and forced convection on the upper and lower surfaces, conduction through the bridge deck, long and short wave radiation, and latent heat processes due to phase changes of water on the top of the bridge deck. Temperatures are calculated for 20 nodes throughout the bridge, including the top and bottom surfaces. The number of nodes is approximately the maximum number of numerically stable nodes for an average bridge. BridgeT outputs values of bridge deck temperature, frost depth and bridge condition (e.g. frosty, icy/snowy, dry). The thermophysical properties of the simulated bridges are specified by the user to maintain program flexibility.

METRo and BridgeT are most similar in the parameterization of conduction and radiation, and least similar in the parameterization of latent heat and convection processes. Freezing and thawing of water on the bridge are instantaneous in METRo, but they can be gradual in BridgeT. BridgeT also has no coupling phase or ability to simulate roadways. METRo uses Monin-Obukov similarity for convective parameterization, whereas BridgeT uses modified Reynolds similarity.

3.1 Initialization and bridge temperature calculation

Initial temperatures are determined for 19 points (nodes) throughout the bridge thickness to reduce error during the beginning hours of the forecast run (Fig. 3.1).

The initial temperatures at interior and bottom nodes are set to the RWIS air temperature and then forced with conduction from the surface node at the top and convection from the bottom while the surface node is maintained at the observed RWIS bridge surface temperature.

Temperature forecasting is very similar to temperature initialization except in forecasting mode, an additional equation is used to forecast the bridge surface node. In forecasting mode, nodes are initially set to the temperatures provided by initialization and re-calculated at each time step based on fluxes from neighboring nodes and atmospheric forcing. Surface node calculations are influenced by radiative and latent heat fluxes, convection, and conduction. The interior nodes experience only conductive transfer. The bottom node experiences both convection and conduction, but not latent heat or radiation because it is assumed that the bottom will stay dry, shielded263 from the sun, and in approximate longwave radiative equilibrium with the surfaces directly under the bridge. The finite difference technique is one-dimensional and explicit. The equations for the nodes have been derived from the energy balance equation,

$$Energy_{in} - Energy_{out} = \Delta Energy_{stored} \tag{3.1}$$

or specifically,

$$q_{conv} + q_{rad} + q_{lat} + q_{cond} = \Delta q_{stored} \tag{3.2}$$

where q is the energy received by a bridge node by the processes of convection, radiation, latent heat, or conduction. By expanding for a node on the bridge-air interface using the definitions of q_{conv} and q_{cond}

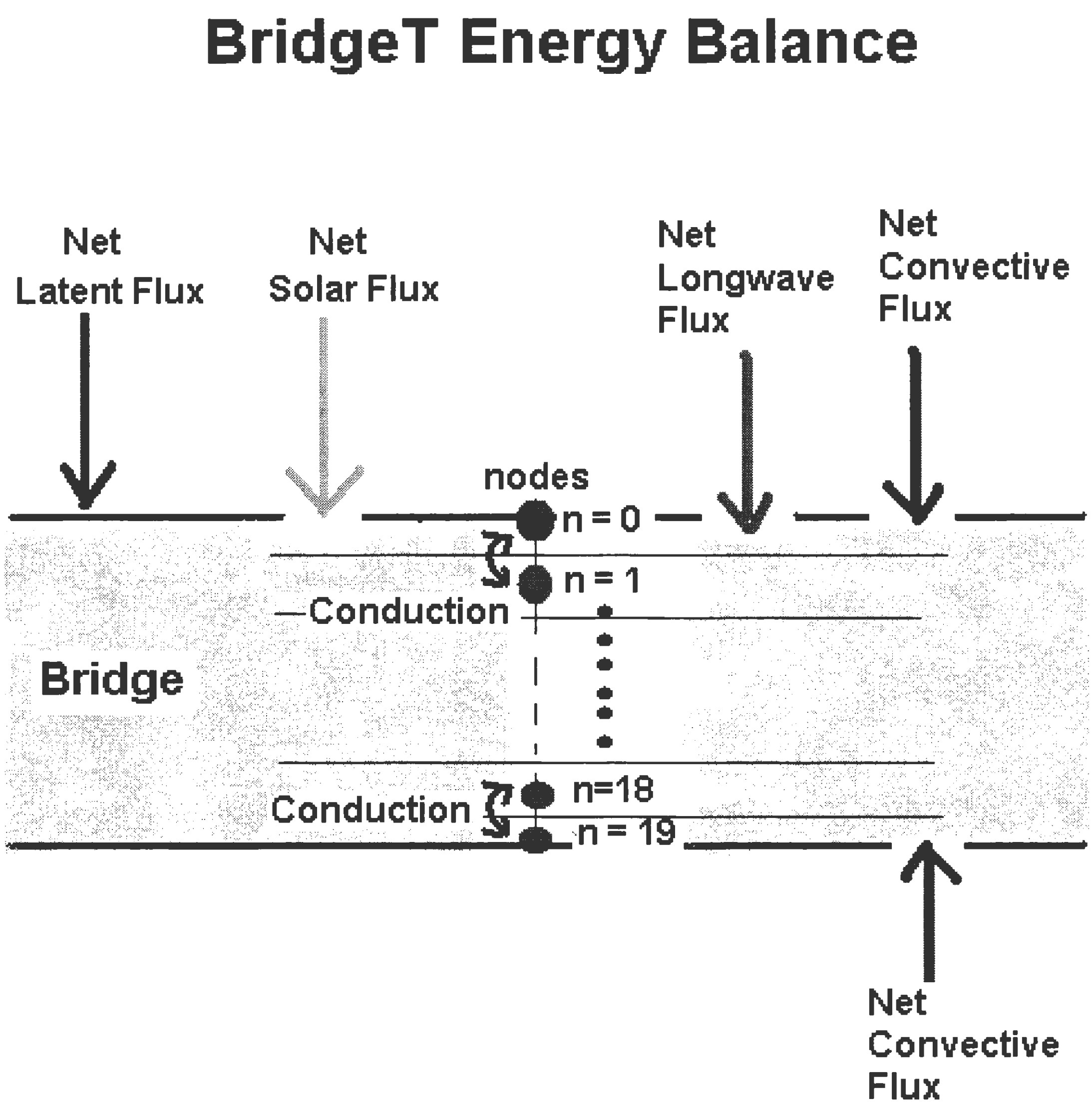

Figure 3.1 BridgeT fluxes and node assignment. The surface node (n= 0) experiences conduction, convection, latent heating, and radiation. Interior nodes experience only conduction. The bottom node (n = 19) experiences conduction and convection. Net fluxes into the slab are considered positive.

$$\left(h(T_a - T) + q'_{rad} + q'_{lat} + k\frac{dT}{dx}\right) Area = \left(\rho c_p \frac{Volume}{2}\right) \frac{dT}{dt} \tag{3.3}$$

The $\frac{Volume}{2}$ on the right-hand side is due to the fact that the volume of bridge material represented by the upper and lower surface nodes are half of the volume represented by interior nodes. h is the coefficient of convection, T is the temperature of the node, T_a is the temperature of the free-stream air, k is the thermal conductivity of the bridge, ρ is density, and c_p is the specific heat of the bridge material (values given in Table 5.1 in Chapter 5). By dividing by area and expanding the differentials for the top node we obtain:

$$h(T_a - T_{t-1}^{n=0}) + q'_{rad} + q'_{lat} + \frac{k}{\Delta x}(T_{t-1}^{n=1} - T_{t-1}^{n=0}) = \left(\rho C_p \frac{\Delta x}{2}\right) \frac{T_t^{n=0} - T_{(t-1)}^{n=0}}{\Delta t} \tag{3.4}$$

$T_t^{n=0}$is the new temperature of the surface node, $T_{t-1}^{n=1}$ is the temperature of the node adjacent to the surface node at the previous time, and $T_{t-1}^{n=0}$ is the temperature of the surface node at the previous time. Solving for $T_t^{n=0}$ yields:

$$T_t^{n=0} = \frac{2}{M}\left(\frac{h * \Delta x * T_a}{k_{bridge}} + \left(\frac{(q'_{rad} + q'_{lat})\,\Delta x}{k_{bridge}}\right) + T_{(t-1)}^{n=1}\right)$$

$$+ \left(1 - \frac{2}{M} * \left(\frac{h * \Delta x}{k_{bridge}} + 1\right)\right) * T_{(t-1)}^{n=0}, \tag{3.5}$$

where

$$M = \frac{\Delta x^2 \rho * c_p}{k * \Delta t} = \frac{\Delta x^2}{\alpha * \Delta t}, \tag{3.6}$$

and α is the thermal diffusivity of the bridge node. The equations for the interior nodes have only conduction

$$q_{cond} = \Delta q_{store} \tag{3.7}$$

thus, the equation for the interior nodes expand to

$$T_t^n = \frac{1}{M}\left(T_{t-1}^{n-1} + T_{t-1}^{n+1}\right) + \left(\left(1 - \frac{2}{M}\right) * T_{t-1}^{n}\right). \tag{3.8}$$

The equation for the bottom node is similar to the equation for the top node, except the bottom node is assumed to be governed by conduction and convection energy balances only. Rearranging (3.1.5) for the bottom node yields:

$$T_t^{n=19} = \frac{2}{M}\left(\frac{h * \Delta x * T_a}{k_{bridge}} + T_{(t-1)}^{n=18}\right) + \left(1 - \frac{2}{M} * \left(\frac{h * \Delta x}{k_{bridge}} + 1\right)\right) * T_{(t-1)}^{n=19}. \tag{3.9}$$

q'_{rad}, q'_{lat}, and h must be calculated before the bridge temperature can be found.

3.2 Convection

The heat flux due to forced and natural convection on the top and bottom surfaces of the bridge are determined by the temperature difference between the bridge surface and the ambient air and a surface convective heat transfer coefficient (h, in $Wm^{-2}K$) which is dependent on the velocity and temperature boundary layers in the fluid. Due to boundary layer development over the finite bridge surface, h depends on position on the bridge relative to the air flow. In BridgeT, the coefficient h is an average over the entire length of the bridge because BridgeT is one-dimensional and cannot utilize horizontal differences in h along the bridge. A length of ten meters is used to represent the length or width of the affected bridge area. The convection calculations use Reynolds similarity which assumes that the wind column affected by the bridge is vertically uniform before encountering the bridge and that the air is incompressible. Figure 3.2 illustrates convective boundary layer development over the bridge and the coordinate system for convective parameterization.

Table 3.1 contains the assumed numerical values of thermo-physical properties of air used in BridgeT's convective parameterization.

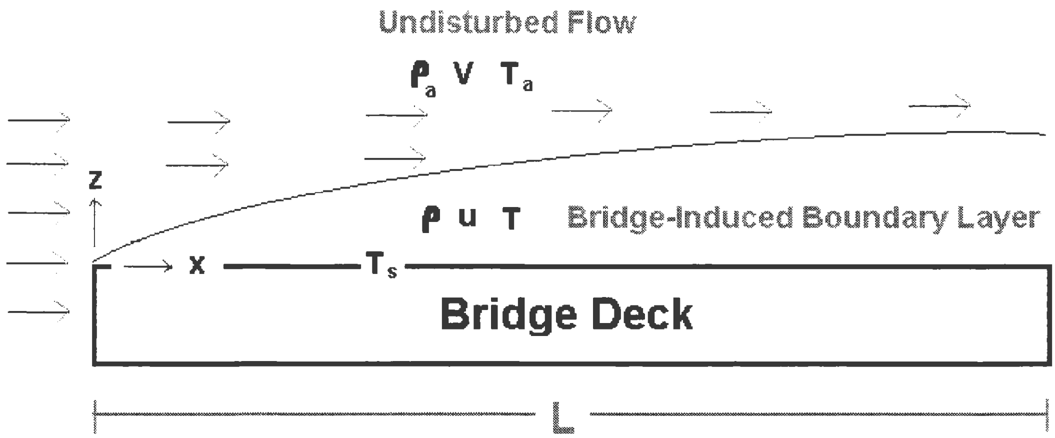

Figure 3.2 Diagram of the bridge-induced boundary layer and key variables used in convective parameterization.

Table 3.1 Thermo-physical values of air as assumed in BridgeT.

Parameter	Symbol	Value
Thermal Diffusivity	α	$2.2{\star}10^{-5}m^2\,s^{-1}$
Kinematic Viscosity	ν	$1.4{\star}10^{-5}m^2s^{-1}$
Thermal Conductivity	k_f	$0.024\ W/m \cdot K$
Pressure	p	$100\ hPa$

h is derived from the equations of the steady-state conservation of energy (3.2.1) and motion (3.2.2) for an incompressible fluid of constant properties.

$$u\frac{\partial T}{\partial x} = \alpha\frac{\partial^2 T}{\partial z^2} \tag{3.10}$$

$$u\frac{du}{dx} = -\frac{1}{\rho}\frac{dp}{dz} + \nu\frac{d^2 u}{dz^2} - g \tag{3.11}$$

The x-direction lies along the plane of the bridge surface, and z is normal to the bridge surface. u is the velocity of the air along the x-direction. ρ is the density of the air, p is pressure, and g is gravity ($9.8\ m\,s^{-2}$). α,ν, and T are the thermal diffusivity, kinematic viscosity, and temperature of the air. It was assumed that the velocity of the fluid along the bridge is much greater than velocities in other directions, and that the change in velocity with height above the bridge is greater than changes along the bridge surface. The thermal gradient normal to the bridge surface is much greater than the gradient parallel to the surface, and heat generation due to viscous dissipation can be ignored.

Using the hydrostatic equation,

$$\frac{dp}{dz} = -\rho_a g \tag{3.12}$$

the equation of motion (3.2.2) can be re-written as

$$u\frac{du}{dx} = g\frac{\rho_a - \rho}{\rho} + \nu\frac{d^2 u}{dz^2} \tag{3.13}$$

ρ_a is the density of the ambient air near the bridge-induced boundary layer. Assuming density variations are due to temperature variations only, the volumetric thermal expansion coefficient, β, can be used to simplify the equation of motion.

$$\beta = \frac{1}{\rho}\frac{\partial \rho}{\partial T} \approx \frac{1}{\rho}\frac{\rho_a - \rho}{T_a - T}. \tag{3.14}$$

Using the Boussinesq approximation,

$$(\rho_a - \rho) = \rho\beta\left(T - T_a\right). \tag{3.15}$$

T_a is the temperature of the air at the top of the bridge-induced boundary layer. (3.2.4) can now be written as

$$u\frac{du}{dx} = g\beta\left(T - T_a\right) + \nu\frac{d^2u}{dz^2}. \tag{3.16}$$

The energy equation (3.2.1) can be normalized by use of dimensionless independent variables

$$x* = \frac{x}{L} \tag{3.17}$$

$$z* = \frac{z}{L} \tag{3.18}$$

where L is the characteristic length of the bridge surface ($10m$).

$$u* = \frac{u}{V} \tag{3.19}$$

$$w* = \frac{w}{V} \tag{3.20}$$

where V is the horizontal velocity of the air upstream of the bridge .

$$T* = \frac{T - T_a}{T_s - T_a} \tag{3.21}$$

T is the temperature of the air at any height in the boundary layer above the surface, T_s is the temperature of the bridge surface, and T_a is the temperature of the undisturbed flow (Fig 3.2). It is assumed that

$$T_s \leq T \leq T_a$$

$$or$$

$$T_s \geq T \geq T_a.$$

Substituting these variables into the energy equation yields

$$u * \frac{dT*}{dx*} = \frac{\alpha}{VL} * \frac{d^2T*}{dz*^2}. \tag{3.22}$$

The term $\frac{\alpha}{VL}$ is a dimensionless parameter defined by

$$\frac{Re}{Pr}. \tag{3.23}$$

The Reynolds number (Re) is a dimensionless coefficient describing the inertial and viscous forces which is proportional to the speed of the wind above the boundary layer formed by the object in the flow. If the wind speed input is 0 $m\,s^{-1}$, it is changed to 0.01 $m\,s^{-1}$ to keep the Reynolds Number from going to zero. The Prandtl number (Pr) is a dimensionless coefficient expressing the ratio of the momentum and thermal diffusivities of a particular substance. The solution for $T*$ is of the form

$$T* = f(x*, z*, u*, Re, Pr). \tag{3.24}$$

The equation of motion can be transformed in a similar fashion;

$$u * \frac{du*}{dx*} = \frac{g\beta\,(T_s - T_a)\,L}{V^2} T * + \frac{\nu}{VL} \frac{d^2u*}{dz*^2}. \tag{3.25}$$

$\frac{\nu}{VL}$is the definition of the inverse of the Reynold's number, and

$$\frac{g\beta\left(T_s - T_a\right)L}{V^2} = \frac{Gr}{Re^2} \tag{3.26}$$

where Gr is the Grashof number; the ratio of the buoyant forces to the viscous forces of the fluid (similar to the Flux Richardson Number).

The solution for $u*$ is now of the functional form

$$u* = f(x*, z*, T*, Re, Gr). \tag{3.27}$$

The solution for $T*$ is dependent on $u*$, so the solution for $T*$ is of the form

$$T* = f(x*, z*, Re, Pr, Gr). \tag{3.28}$$

The surface convective coefficient, h, is defined as

$$h = \frac{-k_f \frac{dT}{dz}}{T_s - T_a} = -\frac{k_f}{L}\left(\frac{Ta - Ts}{Ts - Ta}\right)\frac{dT*}{dz*} = \frac{k_f}{L}\frac{dT*}{dz*} = \frac{k_f}{L} * Nu, \tag{3.29}$$

so the solution to h at the surface of that particular geometry is of the form

$$h = \frac{k_f}{L} * f(Pr, Re, Gr, x*), \tag{3.30}$$

where Nu is the dimensionless temperature gradient and k_f is the thermal conductivity of the air. Averaging h over the length of the surface eliminates the dependence on $x*$ and yields

$$h = \frac{k_f}{L} * \overline{Nu} = \frac{k_f}{L} * f(Pr, Re, Gr). \tag{3.31}$$

From Incropera and DeWitt (2002), $\overline{Nu}$ is comprised of a contribution of the forced flow (wind), plus or minus a contribution from the natural flow (buoyancy forces).

$$\overline{Nu}^3 = \overline{Nu_{forced}}^3 \pm \overline{Nu_{nat}}^3 \tag{3.32}$$

Natural convection suppresses mixing when the temperature profile is stable, and enhances mixing when the temperature profile is unstable.

The dimensionless temperature gradient is calculated as if the flow over the entire bridge surface is turbulent using an experimentally derived relationship between the Reynolds number and the Prandtl number (Incropera and DeWitt 2002).

$$\overline{Nu_{forced}} = A * 0.037 * Re^{0.8} Pr^{\frac{1}{3}} \tag{3.33}$$

A is the convective multiplier which represents the effects of surface roughness, existing turbulence in air flow, and other flow complications due to the bridge structure (e.g., railings, medians, and surface slope). The value for A that yielded the best values using reliable input was 1.5.

$\overline{Nu_{nat}}$ is calculated using Gr and Pr and varies for stable or unstable temperature gradients.

$$Unstable: \quad \overline{Nu_{nat}} = 0.15 * (Gr * Pr)^{\frac{1}{3}} \tag{3.34}$$

$$Stable: \quad \overline{Nu_{nat}} = 0.27 * (Gr * Pr) \tag{3.35}$$

3.3 Precipitation

BridgeT incorporates latent heat effects of water on the bridge and calculates total frost depth by distinguishing between water phases and calculating water fluxes toward or away from the bridge. The maximum amount of water substance that accumulates on the bridge is truncated to a depth of 0.0011 m of liquid water and 0.00063 m (~0.25 inches) of snow accumulation. Excess precipitation is assumed to be removed by runoff or plowing. These limitations will help keep unreasonably high amounts of latent heat effects from influencing the bridge. Bridge conditions (i.e. frosty, dry, wet, icy/snowy, water freezing, water melting) are calculated.

The mass flux toward the bridge (i.e., the condensation/evaporation rate) is positive for condensation or frost deposition and negative for evaporation or sublimation. It is calculated by using the heat-mass transfer analogy that estimates the mass transfer coefficient using the convective heat transfer coefficient. BridgeT distinguishes between frozen or liquid precipitation by the temperature of the air. Precipitation is allowed to freeze, thaw, and evaporate from the bridge. The instantaneous equilibrium temperature between accumulated water and the top bridge node is calculated in all scenarios where precipitation accumulates on the bridge to allow heat fluxes between water substance and bridge. The change in temperature is approximated as instantaneous because one-minute precipitation accumulations are usually small in winter. This approximation does not hold well during heavy-rain events.

If the bridge and precipitation (air) temperature are above 273.16 K, the equilibrium temperature is found and used to find the evaporation/condensation rate. If the precipitation and bridge temperature are below 273.16 K, there is no latent heat effect due to freezing or thawing. Sublimation and deposition of frost are calculated, but sublimation of snow is neglected.

If the bridge temperature is at or below 273.16 K and the precipitation temperature is at or above 273.16 K , the equilibrium temperature is found and determines whether there is evaporation/condensation or freezing of the precipitation. When the equilibrium temperature is above or equal to 273.16 K, there is only evaporation/condensation. When the equilibrium temperature is below 273.16 K, precipitation will begin to freeze. The latent heat flux is calculated by finding the heat flux available from water at a temperature of 273.16 K to equilibrium temperature. The water is assumed to stay at 273.16 K until it is all frozen. The amount of

Table 3.2 Summary of bridge and precipitation temperature requirements for phase changes of water.

Pavement Temp.	Precipitation Temp.	Equilibrium Temp.	Possible Phase Changes
>=273.16 K	> 273.16 K	>=273.16 K	evap., condens.
>=273.16 K	<= 273.16 K	> 273.16 K	melting
>=273.16 K	<= 273.16 K	<= 273.16 K	deposition, sublimation
< 273.16 K	<= 273.16 K	<= 273.16 K	deposition, sublimation
< 273.16 K	> 273.16 K	>=273.16 K	evap., condens.
< 273.16 K	> 273.16 K	< 273.16 K	freezing

ice is calculated by the amount of water that could freeze with the given latent heat in the one-minute interval, added to the previous amount. When the amount of frozen water is equal to the total precipitation volume per unit area, there is no more freezing or latent heat fluxes.

When the precipitation temperature is at or below 273.16 K, but the bridge temperature is above 273.16 K, melting will occur if the equilibrium temperature is above 273.16 K. Melting is calculated in the same way as freezing. When melting occurs, the mass frozen is reduced. The water temperature is kept at 273.16 until all ice has melted. When there is no more frozen mass, the heat flux is zero. The heat flux is also zero when the equilibrium temperature is at or below 273.16 K. Table 3.2 summarizes the freezing/thawing requirements mentioned above.

Frost is allowed to accumulate when there is no existing precipitation or condensation on the bridge. The frost deposition/sublimation rate is calculated by the method used for evaporation/condensation except mass fluxes of frost are determined by vapor pressure over ice, not liquid as is used with condensation or evaporation. Frost depth is calculated by dividing the accumulated frost mass by its density (assumed to be 0.1 times the density of water) and adding the result to the previous total. Frost depth is the depth of frost if it is spread evenly over the unit area. Real frost density and depth may not be uniform across the unit area. The frost depth is reduced to zero if precipitation falls on the bridge, but the water accumulated from the frost deposition remains with the new accumulation as total water depth. If frost or snow is assumed to be present on the bridge, the solar absorptivity is decreased by a factor proportional to the depth of the ice to account for gradual albedo increases through the development of frost or light snow accumulation.

3.4 Radiation

Radiation heat fluxes are determined using surface incident short wave and long wave radiation supplied by the forecast model. Unlike many existing road or bridge models, BridgeT does not derive solar radiation from cloud cover; instead, it receives it straight from the driving model. Long wave radiation lost from the bridge is computed by using the Stefan-Boltzmann relationship

$$q_{lw} = \varepsilon \sigma T^4 \tag{3.36}$$

where q_{lw} is the long wave flux in Wm^{-2}, ε is the long wave emissivity of the bridge (see Chapter 5, Table 5.1), T is the surface temperature of the bridge (K), and σ is the Stefan-Boltzmann constant (= 5.67 $\times 10^{-8}$ $Wm^{-2} \cdot K^4$). Long wave radiation lost from the bridge and radiation reflected by the bridge are subtracted from the total incident radiation to find the net radiative flux toward the bridge.

Chapter 4. Analysis

4.1 Input

MM5 version 3.4, run at Iowa State University, has been used as input for the BridgeT program during the months of November 2003 to March 2004. MM5 is is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model that predicts mesoscale weather circulations. The Iowa State University MM5 has coarse grid resolution of 60 km and fine grid resolution of 20 km. It uses data from the National Centers for Environmental Prediction Eta model for initial and boundary conditions, the Oregon State University Land Surface Model, the Cloud Radiation Scheme, Grell Cumulus Convection, MRF PBL scheme, and Dudhia Simple Ice. MM5 forecasts were issued two times a day, valid at 12 UTC (6:00 am LST) and 00 UTC (6:00 pm LST).

The RWFS model was designed by NCAR for use with a winter road maintenance decision support system. RWFS is designed to maximise forecast accuracy by blending ouput from several numerical weather models (i.e., Eta, aviation, nested grid model) with surface observations and statistical regressions (Bernstein et. al. 2004). It produces 48-hour forecasts eight times daily (00, 03, 06, 09, 12, 15, 18, and 21 UTC). These model runs were available for the months of February, March, and April 1-8.

A desirable method for evaluating the heat transfer (excluding frost calculations) components of BridgeT is to provide it with observed values of shortwave and longwave radiation, temperature, and wind speed and compare its calculated surface temperatures with observed bridge surface temperatures. Fortunately such observations were available through RWIS and radiation observations taken by the USDA National Soil Tilth Laboratory in Ames, IA. Observations of surface incident longwave and solar radiation were taken during the days 09 July 2002 and 11 July 2002 through 19 July, 2002. The radiation observations were taken over a soybean field southwest of Ames, IA, 19 km from the Ames RWIS station. These observations were combined with school-net precipitation observations and RWIS humidity, wind, and 2-m air temperature measurements and used to drive the BridgeT model.

4.2 Observation datasets

Observations used for comparison to the BridgeT model included RWIS bridge temperature observations, as well as early morning bridge frost and bridge temperature observations conducted by human observers on several overpasses in the Ames area.

4.2.1 Frost observations

Frost occurrence was observed for the 2001-02, 2002-03, and 2003-04 frost seasons. Observations were taken on the State Avenue Bridge over Highway 30 near Ames, Iowa during the 2001-02 winter (see Figure 4.1).

For the 2002-03 frost season, County Line Road Bridge and South Dakota Avenue Bridge were added to the observation route. An additional bridge on X Avenue one mile west of County Line Bridge was added to the route during the 2003-04 winter. Multiple bridges allow investigation of spatial variations in frost development and allowed for the continuation of frost observations even if one of the bridges had been treated with de-icing chemicals.

State Avenue Bridge and County Line Road Bridge were selected for close-up observation for this study because they are not routinely treated with frost suppressing materials. They have no on or off ramps for possible turn-around points for IaDOT trucks, thus minimizing

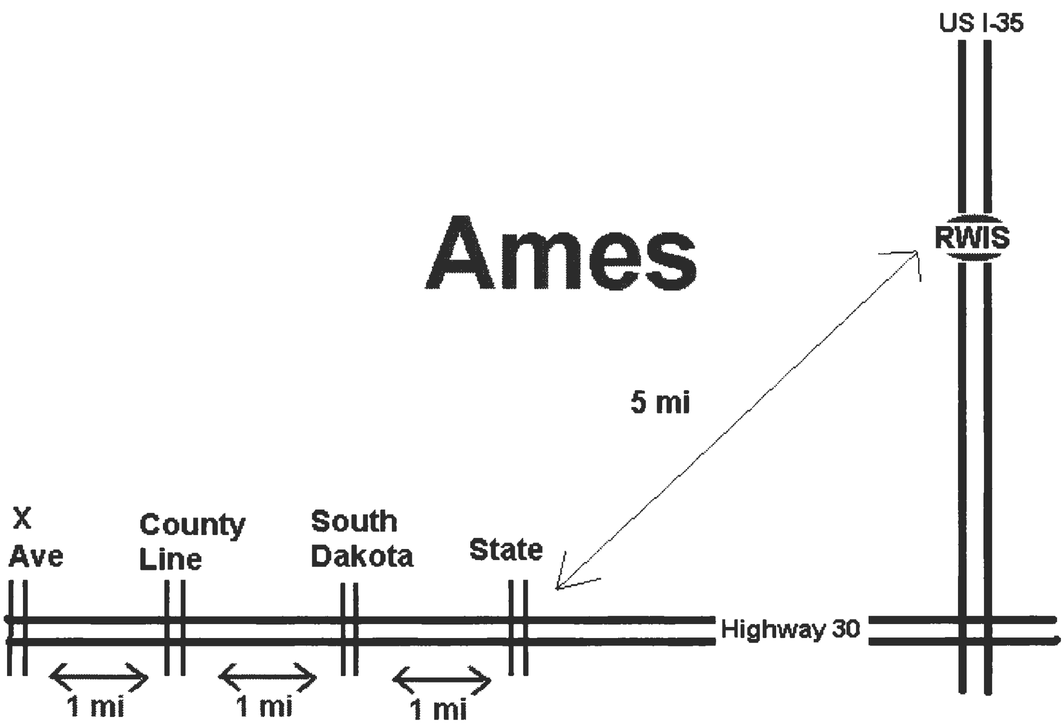

Figure 4.1 RWIS and frost observation sites.

the potential for inadvertent chemical spill from the frost-treatment vehicles. These bridges are typically not as heavily traveled as some other nearby bridges during early morning hours, so bridge observations on foot can be made more safely. The X Avenue bridge is frequently treated for frost, but was easily incorporated into the observation route due to its close proximity to County Line. The South Dakota Avenue Bridge was selected as a drive-over observation site because it is easily checked along the way while traveling between State Avenue and County Line Road. Traffic on the South Dakota Avenue Bridge is too high to allow observations on foot, but frost observations can be made from the vehicle. State Avenue, South Dakota Avenue, County Line Road, and X Avenue bridges are all north-south concrete bridges that allow passage over US Highway 30 at one-mile intervals from east to west, respectively. Terrain in the vicinity of all the bridges is quite flat, with embankments created for the bridge itself being comparable to or greater than natural terrain relief in the immediate area (Figs 4.2 and 4.3).

Flat terrain between bridges minimizes topographically induced influences (drainage flow, shading, wind-tunnel effects, etc.), thereby allowing a cleaner study of natural variability of frost formation.

Each day was considered a candidate for frost, unless there was a very low probability of frost (e.g., nighttime temperatures were greater than 40 °F). Some days were missed due to holidays and snowstorms. The observer visited the bridges beginning at 5:00 AM CST and observed frost conditions both from the car and close-up on foot. While on the bridge on foot, the observers carefully examined the surface for frost and measured the temperature of the bridge surface with an infrared thermometer. The time, date, observations of bridge conditions, general weather conditions, frost characteristics, and surface temperature for each bridge were recorded. If frost was detected, the observer would return periodically until the frost dissipated for follow-up observations and measurements.

It is expected that this method of observation is very accurate, however, there may be

Figure 4.2 State Avenue Bridge observation site and surrounding terrain from the south.

Figure 4.3 View of surrounding terrain near County Line Bridge observation site. The picture was taken near the bridge deck, looking South.

situations (e.g., when frost is very sparse) where frost is present but not visually detected by the observer. These situations would lead to an increased false alarm rate because some actual frost events may be recorded as no-frost events.

4.2.2 Temperature observations

Measurements of bridge surface temperature were made with hand-held infrared thermometers during bridge observation. These observations expose potential differences between RWIS and observed bridge temperatures, thus differences in frost occurrence, between the two sites. In the 2001-02 frost season and the first two months of the 2002-03 season, a Raytek thermometer was used that required calibration before each use and required that the surface temperature be taken within a few inches of the bridge surface. Beginning in mid-January 2003 through the end of the 2003-04 season an Exergen thermometer was used that was emissivity-independent, did not require continuous calibration, but did require that the thermometer aperture be in contact with the surface. Temperature measurement precision (as judged from lack of sensor drift and uniformity across the bridge surface) and accuracy (as judged by comparison with nearby RWIS observations) were higher for the Exergen instrument.

Automated RWIS bridge surface temperature observations are taken from the Interstate 35 overpass over 13th Street on the east side of Ames, IA. The distances from the RWIS site to the State Avenue and County Line Bridge are approximately five and seven miles, respectively. The differences and standard deviations of temperature between the RWIS site and the two bridges over Highway 30 at 5:00 AM shown in Table 4.1 indicate that RWIS surface temperatures are usually a few degrees lower than those taken at the observed bridges. Sensors 1 and 3 are located on the northbound overpass on both lanes. Sensor 2 is located on the northbound overpass passing lane. Instrument error, differences in precipitation accumulation near the sensor (e.g., uneven patches of snow or moisture due to traffic, plowing, or chemical treatments), and

Table 4.1 Average temperature differences (measured bridge temperature minus RWIS sensor measurement) and standard deviations between two observed bridges and three RWIS bridge temperature sensors during the first observation time (35 mornings at 5:00 AM, Exergen instrument only).

Bridge	RWIS Sensor	Mean Temp. Diff. (K)	stDev.
County Line	1	1.05	2.48
	2	2.64	2.37
	3	1.79	2.32
State Ave.	1	1.28	2.43
	2	2.78	2.21
	3	1.95	2.16

shading are possible causes of variations among RWIS temperature sensors.

4.3 Validation methods

4.3.1 Frost

Verification of frost prediction used the first 24 hours of the forecast run to minimize complication due to the possibility of multiple frost predictions in a single 48 hour forecast. Verification also takes into account the ability of the Iowa Department of Transportation (IaDOT) to use the forecast. For instance, a forecast with a 24-hour lead time offers sufficient time for IaDOT to respond, whereas a 12-hour lead time or less may not provide sufficient time for response.

RWFS forecasts were updated eight times per day, and MM5 forecasts were updated twice a day. For this reason, it was possible for many separate forecasts to predict frost for a specific observed frost event. To remove performance dependency on the frequency of newly issued runs, frost forecasts were analyzed according to whether that forecast would elicit a correct assumed response from the IaDOT. If a forecast was issued that forecasts frost within the first 24 hours of the run, the IaDOT could presumably respond to that frost event. If no frost event was forecasted, treatment for frost would not occur. Treatment was assumed to only occur once a day so multiple forecasts predicting frost for a particular morning are assumed to elicit only one treatment. If any of the runs following a false forecasted frost event reverses the frost forecast, the treatment cannot be undone, so that frost forecast is still counted as a false alarm. A frost forecast/response was considered a success if frost was calculated to occur during a time period where frost was seen on any one of the observed bridges. A frost forecast was considered a "miss" when no frost was forecasted and no treatment is assumed to occur, but frost was observed on any of the bridges. A frost forecast and treatment is considered a "partial hit" if frost was forecast to occur in a run within 12 hours of an observed frost event, but the previous runs did not forecast any frost. A treatment like this is not as desirable as one with much better lead time because it would require the IaDOT to accomplish treatment at late hours and possibly within short time frames. Events lasting less than one half hour are considered "short events" which are counted as either partial hits or partial false alarms. These predictions are separated because they often do not have the chance to form deep frost or to be observed.

Conventional measures of forecast skill for binary events include false alarm rate (FAR), probability of detection (POD), miss rate (MISS), rate at which the model will correctly reject the possibility of frost (CR), and threat score (TS). Average absolute error and bias of predicted frost start and end time were compiled for each frost event. Due to the method of observation, 5:00 LST was always the "start" time, though frost was usually present on the bridge by this time.

4.3.2 Temperature

To maintain consistency, it is desirable to use co-located observations of temperature and frost for the evaluation and optimization of BridgeT. Unfortunately, the temperature observations taken during frost observations do not provide a lengthy dataset necessary for a detailed analysis of BridgeT's surface temperature performance. The RWIS site is located several miles from the frost observation sites (see Fig. 4.1), however, RWIS observations are recorded frequently (approximately 2 to 3 times per hour) and provide a more complete standard for comparison. Forecast bridge temperatures were analyzed by comparing RWIS observations from Sensor 1 to the BridgeT forecasts valid only at the time of the RWIS observation. BridgeT outputs results for every minute, whereas RWIS observations are taken much less frequently, so not every BridgeT output value can be used for analysis. Statistics (e.g., bias, root mean square error) are computed for each individual run. Individual model runs were averaged to produce a summary measure of the model's overall performance.

Chapter 5. Results

5.1 Performance using observation input

BridgeT was run with radiation, temperature, and wind speed measurements to test its ability to calculate bridge temperature when given very accurate information. The output of BridgeT was compared against bridge surface temperature measurements as recorded by a nearby RWIS station. The use of observations for input helps reduce the errors in BridgeT calculations that stem from errors in the input so that the accuracy of calculations can be more closely attributed to the abilities of BridgeT itself and the accuracy of the assigned bridge properties. Though the observation set is reliable, it was taken from an agricultural field located about 19 km from the RWIS site so errors due to spatial separation are reflected in BridgeT's calculations. The bridge properties needed by BridgeT to accurately represent a particular bridge include solar reflectivity, long wave absorptivity, bridge thickness, specific heat, density, and thermal conductivity. An additional characteristic is the convective multiplier, A, which coarsely accounts for changes in convection due to the structure of the bridge (e.g., rails and roughness). Bridge thickness was the only known bridge property of the RWIS site bridge. Other bridge properties were determined by trial and error from a set of likely bridge properties. It was found that optimal performance occurred when the bridge properties were set as described in Table 5.1 .

For the entire observational period from 09 July 2002 and 11 July 2002 through 19 July 2002, BridgeT surface temperatures (at approximately 25-minute intervals) were on average 0.20 K

Table 5.1 Bridge properties used by BridgeT during this study.

Bridge Property	Value
Bridge Thickness	0.21 m
Thermal Conductivity	1.401 $W/m*K$
Solar Absorptivity	0.74
Long Wave Absorptivity	0.88
Density	2300 Kg/m^3
Thermal Diffusivity	$6.922*10^{-7} m^2 s^{-1}$
Specific Heat	880 $J/Kg*K$
A	1.5

cooler than RWIS with a root mean square error (RMSE) of 1.90. A plot of BridgeT surface temperature calculations and the observed RWIS surface temperature is shown in Figure 5.1.

The difference between the calculated and observed temperatures is shown in Figure 5.2. Errors frequently occurred during the peak daytime temperature range when the temperature is highly influenced by solar radiation. Small clouds episodically block a portion of the solar radiation from the RWIS bridge surface and radiometers at different times and for different durations due to the physical separation of the two observation sites. Daytime differences occasionally exceeded 5 K, with a peak difference of 7.75 K. Differences during the morning, evening, and nighttime were typically much smaller than the daytime errors. Excluding the intensive solar radiation period (1700 UTC through 2300 UTC) the bias for the observation period was 0.19 K warmer than RWIS and its RMSE was 1.43 K. The morning and evening temperature trends of BridgeT and RWIS observations were usually very similar, thereby providing a measure of confidence in the ability of BridgeT to give accurate temperatures for times of the diurnal period when frost is likely.

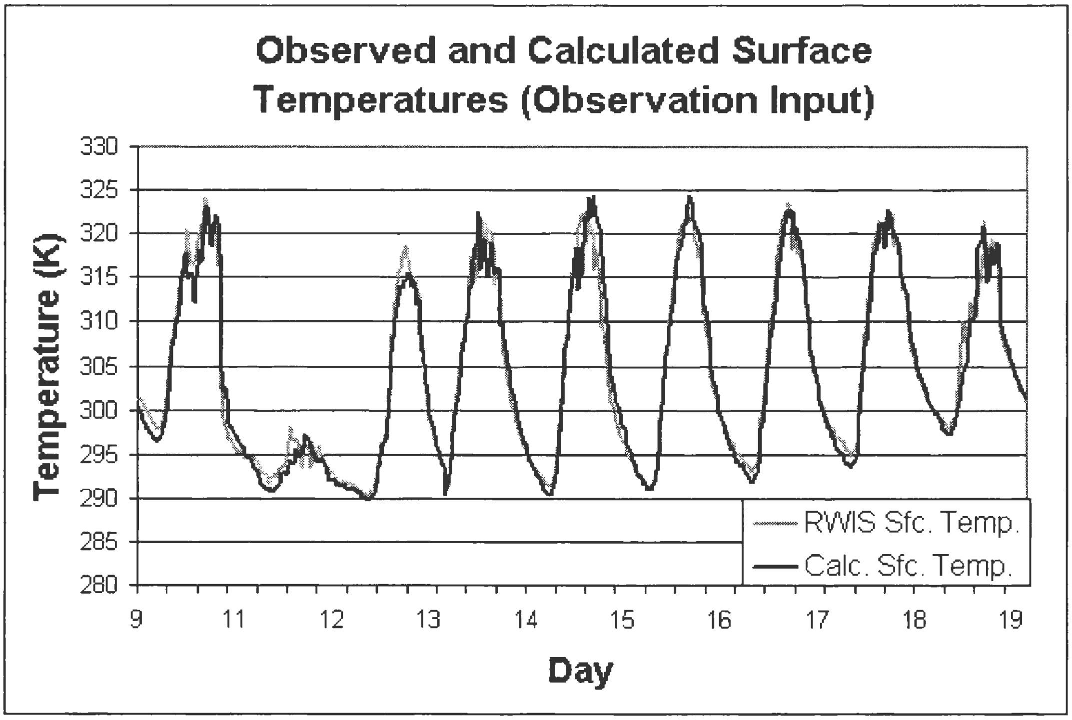

Figure 5.1 Observed (RWIS) and calculated bridge surface temperature for a 10-day period in July 2002.

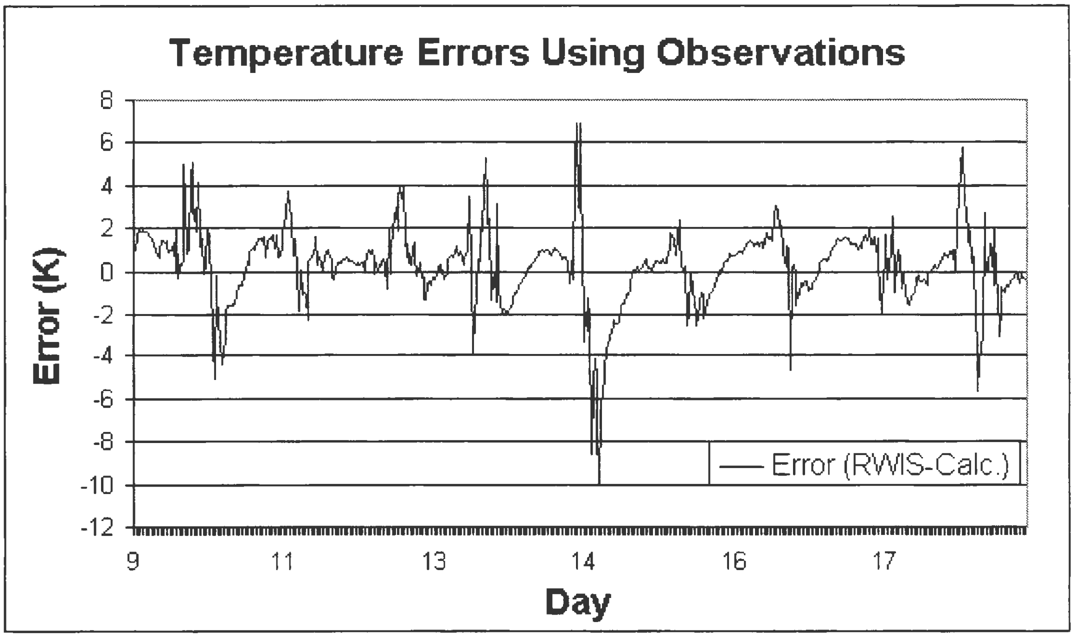

Figure 5.2 Bridge temperature error (RWIS minus calculated) using observational input.

5.2 Performance using model input

5.2.1 Model calibration

Forecast models may have systematic errors in the prediction of certain parameters. Knowledge of the strengths and weaknesses of the driving model may allow forecasters put the results of the BridgeT model into better context or allow them to compensate for recurring biases in the driving model by calibrating BridgeT to the model behavior or by altering the input before using BridgeT. This study includes results from the uncalibrated BridgeT version (as used with the observation input), and calibrated versions optimized for use with particular input models.

5.2.2 RWFS input

455 RWFS model runs were used to drive BridgeT valid for the period from 3 February 2003 through 8 April 2003 for the Ames, IA RWIS site (Fig. 4.1). RWFS-BridgeT produced forecasts that were cold-biased, evident especially through recurring errors in nighttime cooling rates. BridgeT was re-calibrated for use with this particular model to account for systematic biases in the model input. Corrections to the wind speed and long wave radiation yielded the most accurate calculations.

Wind speed errors from the first 100 RWFS runs were used to calculate the wind speed correction to be used with RWFS runs. During the first 100 RWFS runs, the wind speed was on average 1.37 ms^{-1} higher than what was observed at the RWIS site. RWFS-BridgeT forecasts improved when that bias was subtracted from the wind speed of the first 100 and remaining RWFS runs before convection calculations were performed, thus decreasing the convective fluxes. The long wave radiation values were increased by a factor of 1.16 to help counterbalance the steep nighttime cooling rates that occur with the uncalibrated calculations. Figure 5.3 shows a specific forecast before and after calibration.

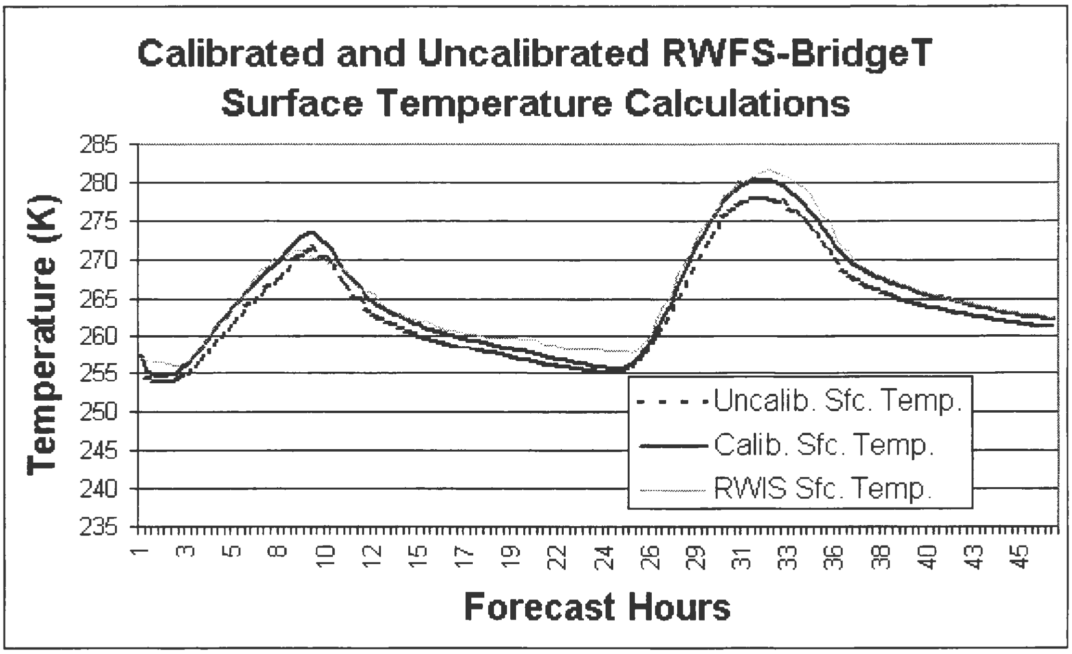

Figure 5.3 An RWFS-BridgeT run before and after calibration compared to observed bridge temperature. Uncalibrated RSME was 2.28 K, calibrated RSME was 1.17 K.

Table 5.2 RWFS-BridgeT frost performance during Feb., March 2003.

	FAR	POD	MISS	CR	POFD	TS
RWFS-BridgeT	0.60	1.00	0.00	0.86	0.14	0.40

Statistical analysis of 48-hr forecasts of the RWFS-BridgeT model runs compared to Ames RWIS observations showed that the average bias and average RMSE of uncalibrated RWFS-BridgeT bridge temperatures for the entire period were 2.03 K and 3.20 K respectively. After calibration, RWFS-BridgeT reduced its overall cold bias to 0.09 K and reduced its average RMSE to 2.64 K. There were 122 forecast runs out of 455 where the calibrated calculation of bridge temperature was actually less accurate compared to its uncalibrated forecast.

The previous BridgeT analysis was calculated using complete 48-hour forecasts. We analyzed BridgeT performance for the first 24 hours of the forecast, the most influential part of the run, because treatment is not usually begun more than a day ahead of a predicted event. Evaluating BridgeT for the first 24 hours also allows comparison with METRo, which was evaluated using 24-hour forecasts. The average error of the first 24 hours of the calibrated RWFS-BridgeT runs was 0.03 K and the RMSE was 2.45 K. The errors in the first 24 hours were better than the errors in the entire 48 hours and the errors were reported to be less than 2 K over 60% of the time. METRo errors were less than 2K over half of the time.

This period overlapped two observed frost events, both of which were forecasted by RWFS-BridgeT . When the forecast period was taken as the first 24 hours of each run, RWFS-BridgeT correctly forecasted the only two observed frost events but predicted three false alarms for this period. There were two mornings where brief frost was predicted to occur one hour after observations were concluded. Table 5.2

contains the frost performance indices for the RWFS-BridgeT runs. There were no partial hits. RWFS-BridgeT correctly predicted 86% of frost and no-frost mornings. This percentage is slightly under Icebreak's (Shao and Lister, 1996) performance (92% of frost and no-frost mornings), however, RWFS-BridgeT performance is based on 24-hour forecasts, whereas Icebreak performance is based on 3-hour forecasts. Its high false alarm and prediction rate corresponds with RWFS-BridgeT's cold bias in early-morning bridge temperature. RWFS-BridgeT average frost start-time for those two events was 2 hours and 10 minutes earlier than the first observation. Its end-times were on average 30 minutes different from what was observed, but had zero bias.

5.2.3 MM5 input

One hundred ninety-eight 48-hour MM5 model runs were used as input for BridgeT during the 2003-04 frost season from 11 Nov. 2003 through 31 March 2004. Uncalibrated MM5-BridgeT surface temperature forecasts were on average 1.02 K too cool during this period and its RMSE was 2.73 K. The cold bias and RMSE improved with calibration for longwave radiation, similar to the longwave calibration used with RWFS. However, MM5-BridgeT did not noticeably improve when wind speeds were calibrated. Wind speed calibration was performed by subtracting the wind speed bias (0.96 ms^{-1}) of the first 50 runs from the wind speed before convection calculations were made. Best results were obtained when longwave radiation was increased by a factor of 1.13. After calibration, the surface temperature bias was reduced to 0.16 K too warm and the RMSE was reduced to 2.64 K. Sixty-nine of 198 MM5-BridgeT forecast runs were actually less accurate after calibration. Calibration was more useful for greater percentage of RWFS-BridgeT runs than MM5-BridgeT runs. Figure 5.4 shows a specific MM5-BridgeT forecast before and after calibration.

Analysis of the first 24 hours of the runs showed MM5-BridgeT was on average 0.13 K too warm and had an RMSE of 2.40 K. Sixty percent of the 24-hour MM5-BridgeT surface temperature calculations possessed errors of less than 2 K.

Frost observations were made on 68 mornings during the winter of 2003-04. Frost was

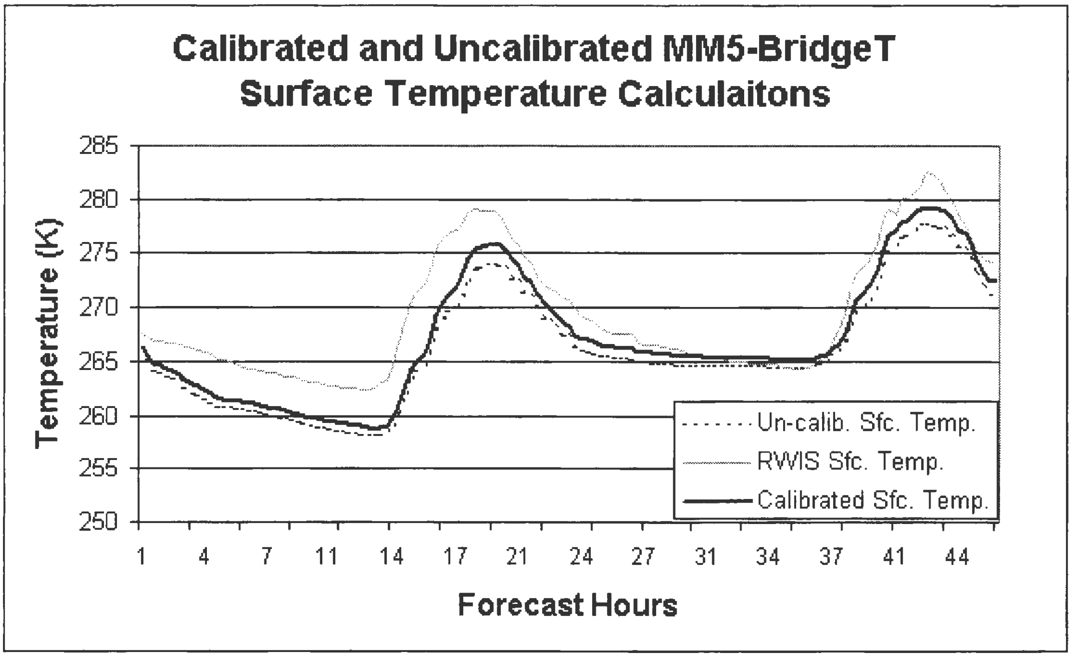

Figure 5.4 An MM5-BridgeT run before and after calibration compared to observed bridge temperature. Uncalibrated RSME was 3.67 K, calibrated RSME was 2.82 K.

positively observed on five mornings. Since MM5 forecasts were available only twice a day, the 1200 UTC run must correctly predict frost occurrence because it determines the frost treatment for that work day. The 00 UTC run can only cause a partial hit because it is issued after the typical work day is concluded, and will not influence treatment schedules except for emergency late-night treatment for the upcoming morning. Thus, overall model effectiveness is largely determined by the quality of the 1200 UTC run.

MM5-BridgeT frost prediction performance was reasonable but had a tendency for false alarms and partial hits. There were 6 false alarms, although one of which was a very short event, lasting less than 10 minutes. Unfortunately, one of the 6 false alarms occurred only on the 00 UTC run, which would call for late-night treatment for no gain. Only one of five frost events was predicted 24 hours in advance due to missing forecasts and precipitation predictions during frost times in preceding forecasts. One frost event was not forecast at all due to the prediction of precipitation during that morning from all associated forecasts. When light precipitation (less than 0.1 $mm \cdot hr^{-1}$) was excluded in BridgeT, all frost events without missing model runs were predicted 24 hours in advance, however, false alarms increased dramatically (20 false alarms). Figure 5.3 shows the performance for standard (light precipitation allowed) and calibrated (light precipitation excluded) BridgeT settings. Despite a poorer prediction rate with BridgeT's standard settings (i.e., light precipitation allowed), predictions of precipitation instead of frost may still cause some response (albeit for precipitation, not for frost) from the IaDOT.

Table 5.3 MM5-BridgeT frost prediction performance during winter 2003-04. The "Standard" setting includes light precipitation. The "- Precip." setting excludes precipitation of less than 0.1 $mm \cdot hr^{-1}$from BridgeT calculations. A short event is a predicted frost event lasting less than 10 minutes. A partial hit is a correct prediction of frost that was issued less than 24 hours in advance.

Setting	Events Included	FAR	POD	MISS	CR	POFD	TS
- Precip.	No short events	0.79	1.00	0.00	0.69	0.31	0.21
- Precip.	Short events	0.80	1.00	0.00	0.67	0.33	0.20
Standard	No partial hits, no short events	0.83	0.20	0.80	0.92	0.08	0.10
Standard	Partial hits and short events	0.60	0.80	0.20	0.90	0.10	0.36
Standard	Partial hits, no short events	0.56	0.80	0.20	0.92	0.08	0.40

The average surface temperature RMSE for the 6 false alarm runs (standard settings) was 2.61 K, slightly better than the average RSME (2.64 K) over all 48-hour runs. This indicates that the surface temperature forecasts were not unusually bad during these false alarm periods. Errors in humidity also contributed to the poor performance. When bridge temperatures were set equal to the observed RWIS surface temperatures, frost was still forecasted during 3 of the 6 false-alarm mornings likely due to errors in humidity input. Calibration of temperature and humidity did not improve overall MM5-BridgeT frost prediction performance.

MM5-BridgeT began frost onset an average 3.9 hours before observations began. Average frost demise was calculated to occur 23 minutes before observations ended.

5.3 Sensitivity

5.3.1 Sensitivity to forecast quality

Input quality is crucial for accurate surface temperature calculations. Except for calibration for biases, BridgeT cannot improve upon the quality of its input and must rely upon the accuracy of the forecast model. Accurate forecasts of bridge condition (e. g., dry, wet, frosty) requires not only accurate input for the calculation of bridge surface temperature, but also accurate meteorological conditions such as humidity and precipitation. Accurate humidity input is crucial to the accuracy of frost predictions because humidity and surface temperature determine if and when vapor will accumulate on the bridge surface. Humidity forecasts are difficult for models to accurately produce and verification is difficult due to sensor accuracy or representativeness (Takle and Greenfield 2002). Input accuracy is determined by comparisons with RWIS and by the quality of the resulting BridgeT forecast.

Figure 5.5 shows the degree of accuracy possible when forecast input for temperature calculation is very accurate. Throughout the 48-hour forecast, the predicted air temperature was within 2 K and the wind speed was within 3 ms^{-1} of observed RWIS values. Radiation predictions were likely accurate because the calculated surface temperatures were very near the observed RWIS surface temperatures throughout most of the 48-hour forecast. Average bias for this day was very small (0.24 K too warm) and the RMSE was only 0.92 K. The greatest error was 2.5 K; occurring during the hottest portion of the first day. Temperature trends during the first day were very good, and the minimum morning temperature was very accurate. The first part of the second day was much like the first, with accurate trends during periods of both heating and cooling. The model underestimated the magnitude of an abrupt temperature drop at 36 hours, but captured the correct trend for the following 6 hours. Only the last 6 hours of the forecast gave substantial errors. Frost occurrence was correctly predicted during the first hours of the forecast.

Figure 5.6 reveals the difficulty BridgeT has in simulating surface temperature when it is supplied with inaccurate information. The forecast accuracy was very good in the first quarter of the run with average errors less than 3 K, but began to produce an excessive temperature rise during the heating portion of the first full day, likely due to errors in cloudiness and solar radiation. Errors due to convection were likely small because the air temperature and wind speed

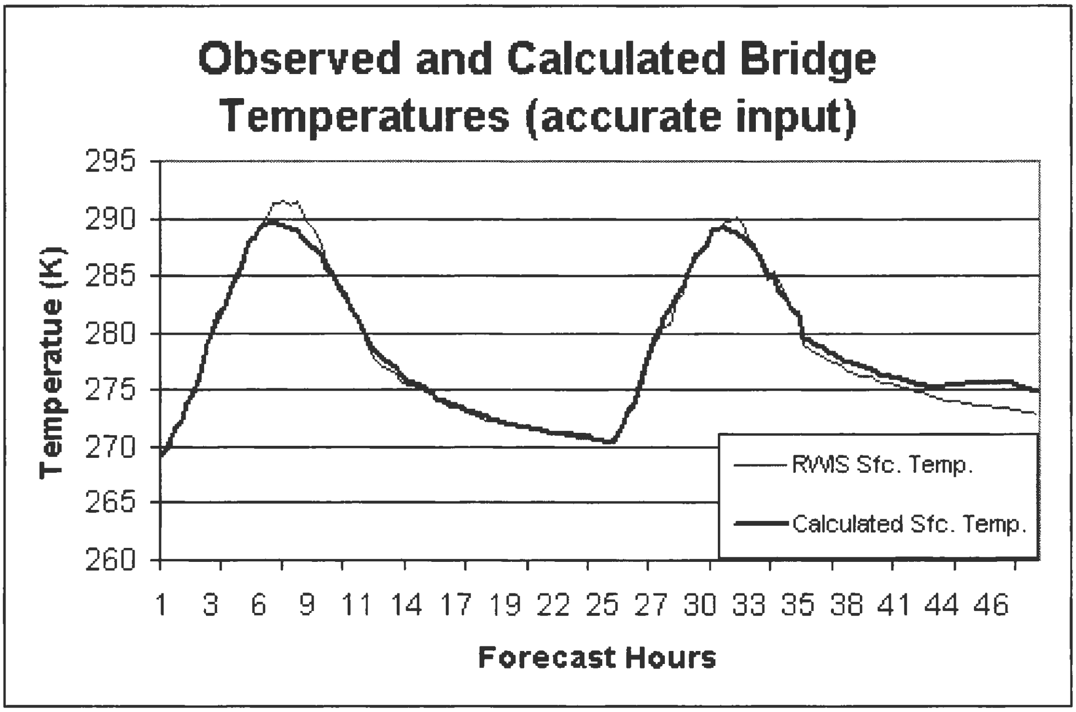

Figure 5.5 Observed and calculated bridge surface temperature using accurate input.

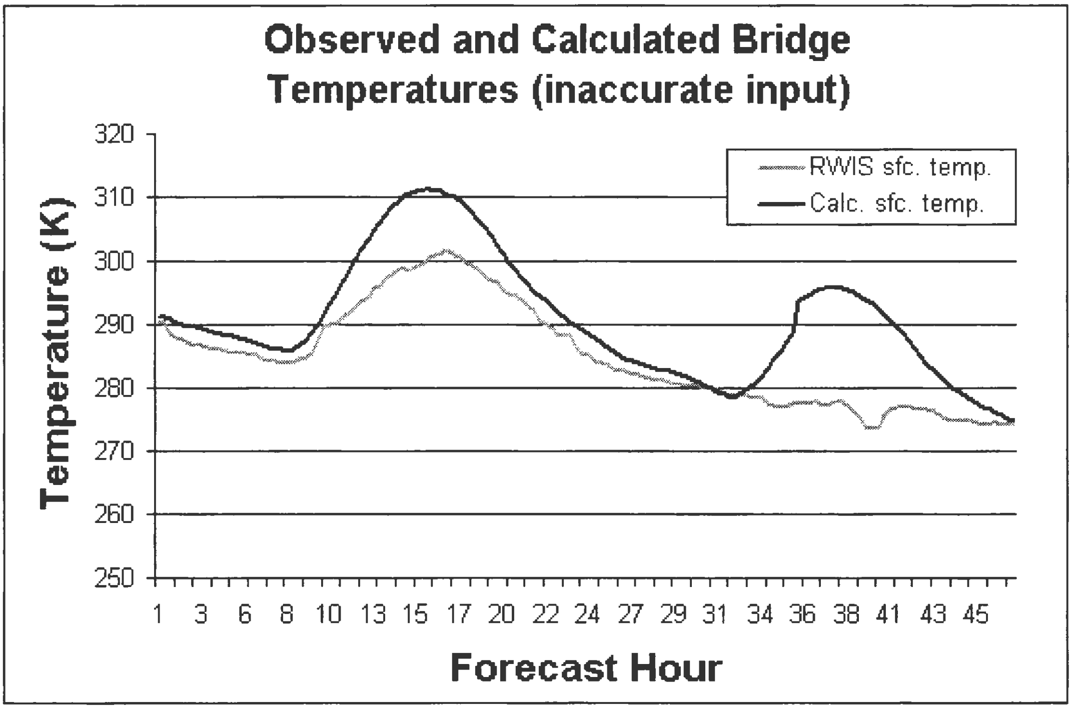

Figure 5.6 Observed and calculated BridgeT surface temperature using inaccurate input.

were very near that observed until later that evening. Surface temperature errors exceeded 10 K during this day. Errors diminished overnight and into early morning of the second day. RWFS and RWFS-BridgeT calculated much higher daytime air and surface temperatures associated with partly sunny skies while the observed temperatures continued to drop as snow and mixed precipitation fell intermittently throughout the second day. Calculated bridge condition during this time was "dry," whereas conditions should have been "wet" or "snowy/icy." Errors during the second day exceeded 19 K. In this example, the average difference between the observations and the RWFS-BridgeT surface temperatures was -5.9 K, with an RMSE of 7.9 K.

Performance of BridgeT is highly sensitive to the quality of its input. BridgeT is capable of producing accurate calculation of bridge surface temperature when supplied with accurate measurements of air temperature, wind speed, and radiation. Model forecasts may be altered by a human forecaster before running BridgeT to investigate the effects of different forecast values on the forecast bridge temperature and frost depth, or to improve upon the forecast model's accuracy. BridgeT accepts text files which can be completely fabricated by the forecaster if no models are available, or if the model's accuracy is questionable, so long as the text file follows the appropriate field format.

5.3.2 Sensitivity to specified bridge properties

Differences in bridge properties occur because bridges are not all constructed identically and concrete itself has a range of thermal and radiative properties because of natural variation due to differences in age, wear, and mixture material or proportion. For these reasons, different bridges may have different properties. For example, a bridge composed of new concrete is much more reflective to solar radiation than an older bridge or one with greater wear even if the bridges are constructed identically. The bridge properties needed by BridgeT include solar absorptivity, long wave absorptivity, bridge thickness, density, specific heat, and thermal conductivity. These properties may be specified to individual bridges if that information is known. It is important to note the impact these specifications have when varied within their usual ranges to investigate the possible effects of incorrect assignment of bridge characteristics, or how different bridges will react under identical weather conditions.

These sensitivity studies were conducted to determine the effects variable bridge properties (i.e., solar absorptivity, longwave absorptivity, thermal conductivity, and bridge thickness) have on BridgeT forecasts by varying them to the extremes of their usual values. To aid the isolation of the effects of a particular characteristic, the variable studied is varied to its high and low extremes while the remaining variables are held constant (values in Table 5.1). The variable characteristics may be studied independently because the specified bridge properties are static and have no relation to each other, however, thermal diffusivity must be varied with conductivity because they are linearly related. The observed radiation, temperature, and wind data (see Section 5.1) were used to drive the model during this study.

5.3.2.1 Bridge property sensitivity results

Figure 5.7 was compiled using the first few days of the sensitivity data set (see Figure 5.1). It illustrates the temperature differences resulting from altering certain variables to their extreme values while the other values are maintained at the values specified in Table 5.1.

Increased solar absorptivity increases surface temperature by increasing the fraction of solar radiation that is absorbed by the bridge. Low values of absorptivity lead to cooler bridge surfaces, especially during very sunny days. Solar absorptivity has no direct effect during the nighttime when there is no shortwave flux, however the effects of absorptivity may be apparent for several hours after solar heating has stopped because of thermal inertia from daytime heating. The effects of solar absorptivity are relatively small during very overcast days because the reduced solar flux. The smallest daytime solar absorptivity temperature differences in Figure

5.7 occurred during a cloudy, rainy day when solar radiation was at a relative minimum. Of the parameters studied, solar absorptivity has the largest impact on bridge temperature due to the large range in possible absorptivity values (0.6 to 0.8) and the large yet variable (0 to 1000+ Wm^{-2}) energy flux that is received from the sun.

Longwave (LW) absorptivity determines the percentage of incoming infrared radiative flux that will be absorbed by the bridge and the percentage of blackbody radiation that will leave the bridge. Opaque substances absorb with the same efficiency as they emit, so higher absorptivity of LW radiation leads to higher gain of LW radiation from the atmosphere but a higher loss of radiation from the bridge. High absorptivity leads to a net loss of LW radiation from the bridge because the bridge is usually at a much higher temperature than the radiating temperature of the atmosphere; thus a bridge will radiate more energy than what it receives. Reduced LW absorptivity leads to less net radiation loss from the bridge. The effects of possible LW absorptivities are small but can be seen at all hours of the forecast and do not vary much in the diurnal cycle (Fig. 5.7). The effects of changing LW absorptivity are the smallest among the effects of the four bridge properties because it is allowed a small range (7%) in possible values.

Bridge thickness determines the rates at which a bridge heats, and hence its thermal inertia. Greater thickness keep the surface closer to the recent bridge temperature because there is a larger mass of bridge to heat or cool through conduction. Thinner bridges react more promptly to external forcing because they have less mass and thermal inertia. This is apparent in Figure 5.7 through a several-hour time shift (when compared to other diurnally cycling variables) in maximum temperature differences. The magnitude of temperature change with change in thickness is small and mostly apparent at night and early morning when strong solar fluxes are not present.

Thermal conductivity determines the bridge's ability to transfer heat between bridge particles. High conductivity allows heat to transfer to other bridge levels more easily which reduces internal temperature gradients. Low conductivity isolates the layers and allows them to heat or cool more independently of a nearby layer. The effects of conductivity differences are the second largest among the four physical properties. However, high (low) conductivity produces negative (positive) surface temperature tendencies when the bridge is heating, and positive (negative) when the bridge is cooling, (see Fig. 5.7) so conductivity has a small effect on the time-averaged bias of the model.

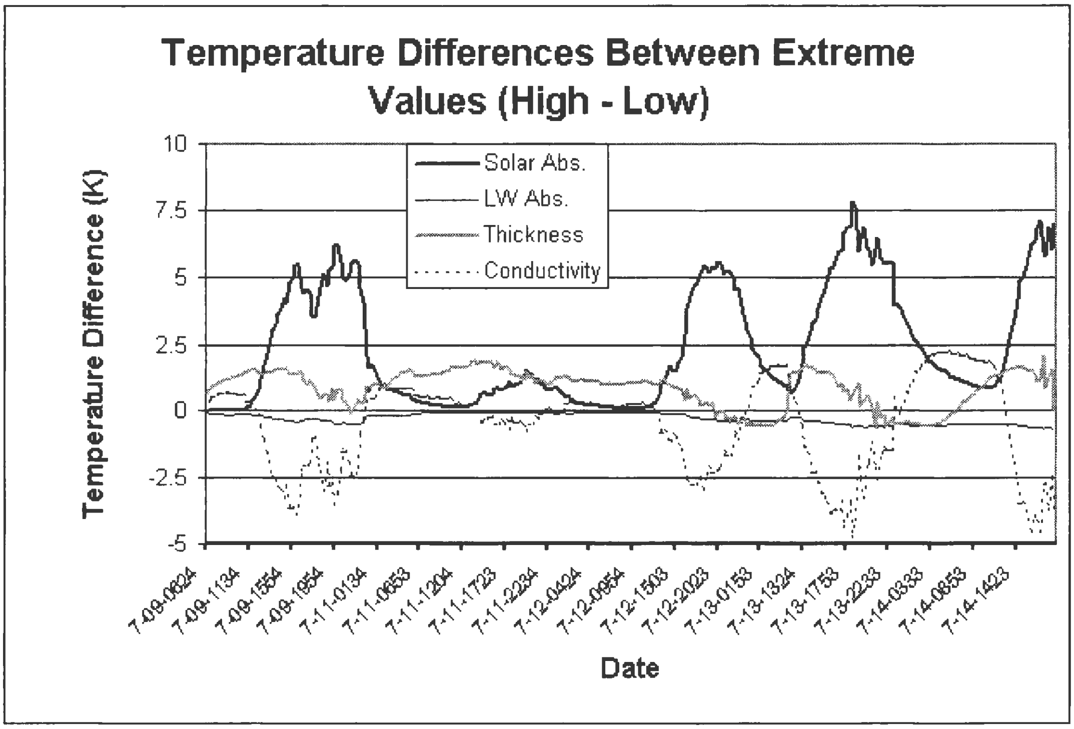

Figure 5.7 Surface temperature differences between BridgeT calculations using high and low bridge characteristic values. Lines indicate the temperature difference calculated when the labeled characteristic is changed from high to low while the other characteristics are held constant. This graph is constructed from data from the first five days of the observation data set (see Figure 5.1). The magnitude of these effects will vary seasonally.

Chapter 6. Summary

Frost occurs several times per year on Iowa bridges, which may create hazardous conditions for motorists. Frost forecasts help roadway maintenance crews decide when and where frost suppression chemicals should be used. Accurate bridge frost forecasts depend on accurate predictions of bridge surface temperature, air temperature, wind speed and humidity.

BridgeT was designed to help forecasters produce accurate forecasts of bridge frost and condition. BridgeT is a numerical model for heat transfer in a concrete bridge that takes atmospheric values from a weather forecast model and calculates bridge surface temperature, frost depth, and bridge conditions. It accounts for heat fluxes due to solar and longwave radiation, conduction through the bridge, convection on the top and bottom surfaces, and latent heat effects through explicit forward-difference numerical methods. BridgeT is similar to METRo, a road and bridge model developed by Crevier and Delage (2001), although there are differences in the parameterization of turbulent convective flow and the phase changes of water. BridgeT is flexible as to the origin of the forecast used for calculation, whether it be from a computer model or created or altered by a human forecaster.

Comparisons of its results with measured surface temperatures from an RWIS station have demonstrated that BridgeT realistically represents early-morning low temperatures and temperature trends when run with input from observations of air temperature, wind speed, and radiation. Average BridgeT surface temperature error using observations was 0.25 K warmer than the RWIS observations. Some of the error can be attributed to spatial separation (19

Table 6.1 RWFS and MM5-BridgeT performance.

Input	Events Included	FAR	POD	MISS	CR	POFD	TS
MM5	No short events, no light precip	0.81	1.00	0.00	0.65	0.35	0.19
MM5	Short events, no light precip	0.82	1.00	0.00	0.62	0.38	0.17
MM5	No partial hits, no short events	0.90	0.20	0.80	0.84	0.16	0.08
MM5	Partial hits and short events	0.75	0.80	0.20	0.80	0.20	0.24
MM5	Partial hits, no short events	0.71	0.80	0.20	0.84	0.16	0.27
RWFS	All	0.60	1.00	0.00	0.86	0.14	0.40

km) of the bridge temperature observation site and the radiation observation site. BridgeT is capable of supplying surface temperatures within 1K of measured values over a 40-hour forecast period if it is supplied with accurate weather forecasts. RWFS-BridgeT has shown reasonable skill in surface temperature and frost prediction although the nighttime cooling rate is typically too steep, likely due to RWFS long wave radiation errors. Calibrated RWFS-BridgeT surface temperature performance is similar to that of METRo. RWFS-BridgeT tends to over-predict frost but also has a high probability of predicting all frost events. These traits are consistent with the steep nighttime temperature trends associated with RWFS-BridgeT. MM5-BridgeT has shown slightly better skill in bridge temperature prediction; although calibration improved overall performance, calibration was not as effective at improving the forecast as was true for RWFS-BridgeT. MM5-BridgeT temperature performance is also similar to that of METRo. Frost predictions were prone to false alarms and partial hits, largely due to humidity and precipitation errors from MM5. Calibration for frost performance was not effective. Table 6.1 shows the performance of RWFS- and MM5-BridgeT frost forecasts.

Sensitivity studies were performed to investigate the effects of input quality and bridge property specification. Model performance is particularly sensitive to radiation input because a large proportion of the total energy transfer at the bridge surface is through solar and long wave absorption or emission. Bridge condition forecasts rely on accurate forecasts of surface temperature, humidity, and precipitation. BridgeT can use site specific information about bridge characteristics to improve local forecasts. Forecasts are most sensitive to the possible variations of solar reflectivity and thermal conductivity and are least sensitive to differences in long wave absorptivity and bridge thickness.

Future improvements to BridgeT may include fine-tuning and testing its pavement condition forecasts, expanding BridgeT for roadway use, and incorporating treatment recommendations for predicted pavement conditions. Since BridgeT cannot improve upon the quality of its input, it remains vulnerable to failure through input errors, regardless of the level of BridgeT's sophistication. Improvements in mesoscale forecast quality, especially humidity and radiation accuracy, are necessary for significant improvements to BridgeT frost and surface temperature forecasts.

APPENDIX A. Measures of forecast skill for binary events

Takle (1990) and Knollhoff (2003) provide discussion of measures of skill for binary events applied to frost forecasting.

FAR is the number of false-positive treatments(forecasted frost when there was none) divided by the number of all frost predictions. FAR is the probability a given treatment is a false alarm. It ranges from 0 (good performance) to 1 (bad performance).

POD is the number of correct frost treatments divided by the number of all frost events. POD is the probability that a frost event will be correctly forecasted and treated. It ranges from 0 (bad performance) to 1 (good performance).

MISS is the number of frost events that occurred but were not predicted divided by the number of all frost events. MISS rate is the probability that a given frost event was not calculated. It ranges from 0 (good performance) to 1 (bad performance).

CR is determined by the ratio of the number of correct no-frost predictions to the number of times where no frost was observed. It is the probability that a no-frost event will be correctly predicted. It ranges from 0 (bad performance) to 1 (good performance). CR can be inflated by including a dataset which includes many days where frost had little chance of occurring. CR and POFD add to 1.0.

POFD is defined as the probability that a no-frost event will be incorrectly forecast as a frost event. POFD is found by the ratio of false alarms to the number of times where no frost was observed. It ranges from 0 (good performance) to 1 (bad performance). POFD can be reduced by including a dataset which includes many days where frost had little chance of occurring. CR and POFD add to 1.0.

TS is calculated as the number of correct frost treatments divided by the sum of the total frost treatments and the number of frost events that occurred but were not predicted. The previous measures only describe one portion of the model's skill. TS is a measurement of how well the model performs overall by combining the different performance areas. It ranges from 0 (bad performance) to 1 (good performance).

APPENDIX B. BridgeT model code

```
// Tina Greenfield
/* This program is designed to calculate a concrete bridge's surface temperature.
It is initialized with RWIS bridge and air temperatures, all else from MM5
or some other weather model. MM5 supplies atmospheric conditions at
regular intervals, which are used to force the bridge temperature. MM5
values are not altered in this program */

#include <iostream.h>
#include <fstream.h>
#include <string>
#include <iomanip.h>
#include <stdlib.h>
#include <math.h>
#include "RWIS.h"

float radiative( float, float, float, float, float,float );
float convection( float, float, float );
```

```
float initialize( float, float, float, float, float, double, int, int );
float precipitation( float, float, float, float, float, float, float, float, float,float &,
float &, float &, int &, int );
float evaproation ((float, float, float, float, float, float);
float bridgelevels( float, float, float, float, float, float, float, double, int, int );

int main (int argc, const char * argv[])
{
  if (argc != 4)
  {
    cerr << "usage: bridgemodel <rwis file> <mm5 file> <bridgeProperties>" << endl;
    return 1;
  }

  allRWIS rwisfile( argv[1] );
  ifstream mm5file( argv[2] );
  ifstream bridgeProperties( argv[3] );

  // returned values from functions residual, convection, frost,
  // precipitation, initialize,and bridgelevels
  float radiation, h, frostDepth, bridgeTemp, latentFlux, rwisAir;
  float initialTemp;
  int condition;

  //stuff from MM5
```

```
float oSWradiationIn,oLWradiationIn, oprecipRate, otempA, owind, oqa;
//"old" values for interpolation
float nSWradiationIn,nLWradiationIn, nprecipRate, ntempA, nwind, nqa;
//"new" values for interpolation
float cSWradiationIn,cLWradiationIn, cprecipRate, ctempA, cwind, cqa;
//"current" values from interpolation
nprecipRate = 0.0;
float minutesf; // stuff for model interpolation
int oldMinutes;
float difference;

//timestamp stuff. Updates the timestamp for interpolated values.
int year, month, day, hour;
int yearO, monthO, dayO, hourO;
float junky;
char junk;

//stuff from the property file. Bridge thickness, solar absorptivity
//longwave absorptivity, conductivity, density, and specific heat
float thickness, swAbs, lwAbs, kbridge, density, cp;
float thermalDiffusivity;

if( mm5file.good() == false )
{
  cerr << "Can't open file " << argv[2] << endl;
```

```
    exit( 1 );
}
if( bridgeProperties.good() == false )
{
    cerr << "Can't open file " << argv[3] << endl;
    exit( 41 );
}
ofstream outfile( "pavetemp.out" , ios::out);
if (!outfile)
{
    cerr << "file could not be opened: " << endl;
    exit (2);
}

bridgeProperties>>thickness>>kbridge>>swAbs>>lwAbs>>density>>cp;
thermalDiffusivity = kbridge / (density * cp);
// initializing the bridge deck layer temperatures
int initialcounter = 1;
for ( int i = 0; i < rwisfile.TotalMinutesInFile(); i++ )
{
    RWISdata currentData;
    currentData = rwisfile.DataAtMinutesFromStart(i);
    bridgeTemp = currentData.surfaceTemp;
    h = convection(currentData.wind, currentData.airTemp, currentData.surfaceTemp);
    for ( int c = 0; c < 19; c++)
```

```
    {
        initialTemp = initialize( bridgeTemp, currentData.airTemp, h, kbridge,
        thickness, thermalDiffusivity, c, initialcounter);
    }

    initialcounter = initialcounter + 1;
    rwisAir = currentData.airTemp;
}
// All RWIS initialization is done.

// Beginning of loop for calculations for forecasted bridge temperature
int linecounter = 0;
int check = 0;
int z = 0;//minutes keeper
float zz = 0;//minutes between model values

while( mm5file>>year>>junk>>month>>junk>>day>>junk>>hour>>
junk>>junky>>minutesf>>ntempA>>nqa>>nwind>>nSWradiationIn>>
nLWradiationIn>>nprecipRate )
{
    int minutes=(int)minutesf;
    if ( linecounter == 0 && fabs(ntempA - rwisAir) > 15.0 )
    {
        cerr << "15+ gap MM5& input air temperature " <<
        ntempA<<" "<<rwisAir<<endl;
```

```
  return 23;
}

// mm5 data is hourly. It needs to be interpolated for minute by minute.
if ( linecounter != 0 )
{
  // slope-point for the minute by minute data
  difference = minutes - oldMinutes;
  while ( z < minutes )
  {
    zz = z - oldMinutes;

    cqa = ( nqa - oqa ) / ((float) difference) * (zz) + oqa;
    cwind = ( nwind - owind ) / ((float) difference) * (zz) + owind;
    cSWradiationIn = ( nSWradiationIn - oSWradiationIn ) /
    ((float) difference) * (zz) + oSWradiationIn;
    cLWradiationIn = ( nLWradiationIn - oLWradiationIn ) /
    ((float) difference) * (zz) + oLWradiationIn;
    cprecipRate = ( nprecipRate - oprecipRate ) / ((float) difference) *
    (zz) + oprecipRate;
    ctempA = ( ntempA - otempA ) / ((float) difference) * (zz) + otempA;

    // quality checks
    if ( ctempA > 410 || ctempA < 200 )
    {
```

```
  cerr << " bad MM5 air temperature input " <<ctempA<< endl;
  return 4;
}
if ( cqa > 1 || cqa < 0 )
{
  cerr << " bad MM5 humidity input " << cqa<<endl;
  return 5;
}
if ( cwind > 70 || cwind < 0 )
{
  cerr << " bad MM5 windspeed input " <<cwind<< endl;
  return 6;
}
if ( cSWradiationIn> 1000 || cSWradiationIn < 0 )
{
  cerr << " bad MM5 SWradiation input "<<cSWradiationIn<< endl;
  return 7;
}
if ( cLWradiationIn> 2000 || cLWradiationIn < 50 )
{
  cerr << " bad MM5 LWradiation input " << cLWradiationIn << endl;
  return 8;
}
if ( cprecipRate > 40 || cprecipRate < 0 )
{
```

```
    cerr << " bad MM5 precipitation input " <<cprecipRate<< endl;
    return 9;
}

//calling functions
h = convection(cwind, ctempA, bridgeTemp);
latentFlux = precipitation(cprecipRate, h, ctempA, cqa, cwind,
kbridge, thickness, density, cp, bridgeTemp, frostDepth, swAbs,
condition, check );
radiation = radiative(cSWradiationIn, cLWradiationIn, bridgeTemp,
swAbs, lwAbs, ctempA);
bridgeTemp = bridgelevels(radiation, latentFlux, bridgeTemp,ctempA,
h, thickness, kbridge, thermalDiffusivity, check, z );
check++;

// calculating dew point temperature for output purposes only.
float Td;
Td = 5.42*pow(10,3) / (log( 2.53 * pow(10,8) * 0.622 / ( cqa * 100.0)));

if(hourO == 24)
{
    hourO = 0;
    dayO++;
}
//writing the calculated bridge temperature to file.
```

```
//different outputs to make timestap correct
outfile << yearO <<"-"<<monthO<<"-"<<dayO<<"_"<<hourO <<":"
<< ( (z%60) < 10 ? "0" : "" ) << (z%60) << " "
<< ctempA<< " " << cwind << " "<<cSWradiationIn<<" "
<<cLWradiationIn<<" "<<h<<" "<<latentFlux<<" "
<< bridgeTemp << " "<<frostDepth << " "<<Td << " ";

switch (condition)
{
  case 1:
    outfile<<"frosty";
    break;
  case 2:
    outfile<<"Icy/Snowy";
    break;
  case 3:
    outfile<< "Melting";
    break;
  case 4:
    outfile<<"Freezing";
    break;
  case 5:
    outfile<<"Wet";
    break;
  case 0:
```

```
            outfile<<"Dry";
            break;
        }
        outfile<< endl;
        z++;// sends it through the minute loop again unless its at the next hour
      }
    }

    //turn the "new" data into the "old" data
    otempA = ntempA;
    oqa = nqa;
    owind = nwind;
    oSWradiationIn = nSWradiationIn;
    oLWradiationIn = nLWradiationIn;
    oprecipRate = nprecipRate;
    yearO = year;
    monthO = month;
    dayO = day;
    hourO = hour;
    linecounter = linecounter + 1;
    oldMinutes = minutes;
    z = oldMinutes;

} // end of bridge surface calculator loop.
outfile.close();
```

```
  return 0;
}//end of main


float initialize( float bridgeTemp, float tempA, float h, float kbridge,
float thickness, double thermalDiffusivity, int c, int i )
{ /* this function is used to initialize the bridge layer temps before the
  forecasted temperatures are calculated. It uses the RWIS air and surface
  temperatures to force the lower level temperatures since only the surface
  temperature is actually measured. It runs using the previous surface
  and air temperatures.*/

  static float nexttempB[19];// array to temporarily store the new values so
  //they dont interfere with the following calculations.
  static float tempB[19];
  // returns the calculated value to "bridgelevel" and skips any additional calculations
  if ( i == 0 )
  {
    return tempB[c];
    // array to store the node temperatures. Initially set to airTemp.
  }
  static float depth;
  depth = thickness / 19.0; // distance in meters between nodes
  static const float M = ((depth * depth) / (thermalDiffusivity * 60.0));
  // unitless coefficient for heat transfer rates in concrete.
```

```
    if ( i == 1)
    {
        tempB[c] = tempA ;
    }
    else
    {
        nexttempB[0] = 1 / M * ( bridgeTemp + tempB[1] ) +
        ( 1 - ( 2 / M ) ) * tempB[0];
        if ( c > 0 && c < 18 )
        {
            nexttempB[c] = 1 / M * ( tempB[c-1] + tempB[c+1] ) +
            ( 1 - ( 2 / M ) ) * tempB[c];
        }
        nexttempB[18] = (2 / M) * (h * depth / kbridge * tempA + tempB[17]) +
        (1 - (2 / M) * (h * depth / kbridge + 1)) * tempB[18];
        tempB[c] = nexttempB[c];
    }
    return tempB[c];
}

float precipitation( float precip, float h, float airTemp, float qa, float wind,
float kbridge, float thick,float concreteDensity, float Cc, float &bridgeTemp,
float &frostDepth, float &abs, int &condition, int i )
{ /* MM5 calculates precip rate in centimeters per hour, and the bridge will not
```

hold all the water that falls on it. This function divides the precip rate into kilograms per minute, calculates total precip. accumulation, and truncates the precip amount if more were to fall than the bridge will hold. The truncation will help keep unreasonable amounts of water from cooling the bridge through latent effects. The evaporation rate and latent heat effects are calculated and the heat flux is returned to main. The total frost depth is calculated.*/

```
static const float waterDensity = 1000 ; //kg m-3
static const float cp = 1007 ; // specific heat of air J/(kg k)
static const float Le = 0.907;//Lewis#=thermal diffusivity of water / mass diffusivity
//approximately constant. Le = Lewis # raised to the 2/3 power.
static const float R = 0.08314; // m3 bar/ kmol K Universal gas constatant
static const float M = 18.0; // Kg/Kmol molecular weight of water.
static const float epsilon = 0.622; //constant Ratio of mol. weight of water/dry air
static const float Lf = 3.34 * pow ( 10,5); //latent heat of freezing J/kg
static const float Lv = 2.5 * pow ( 10,6); //latent heat of condensation J/kg water
static const float Cw = 4218 ; // J/K kg specific heat of water
static float thickness;// depth of the top concrete layer
thickness = thick / 38.0;
static float Mc;// mass of concrete in one node layer per unit area kg
Mc = concreteDensity * thickness;
static float Tw; // temperature of the water already accumulated on the bridge
static float precipDepth; // meters
static float frozen; // depth of water that is frozen on the bridge
static float totalDepth; // total depth of water accum. Includes condensation/frost
static float Mw; // per unit area mass of existing accum.
```

```
Mw = (precipDepth) * waterDensity ;
float evapRate; // kg s-1 m-2
float Patm;// pressure of water vapor in the surrounding air
static float oldabs;//original solar absorptivity
Patm = qa / epsilon; // * 1000mb - 'in bars
float airDensity; // density of air = p/(RT) kg/m3 assuming pressure = 1000 mb
airDensity = 100000/ ( 287 * airTemp);
float hm; // mass transfer coefficient
hm = h / (airDensity * cp * Le );
float Mf; // per unit area mass of water that just fell as precip
float Te; // equilibrium temp of bridge and fallen precip
float heatFlux; // latent heat flux lost or gained to the bridge. Returned to residual
float freezeRate; // kg/s of water freezing or melting.

evapRate = 0; // makes sure evapRate is not carried over from last iteration
heatFlux = 0;
precip = precip / 6000.0 ; // centimeters per hour to meters per minute
Mf = precip * waterDensity ;

if ( i == 0 ) // sets initial depth to zero
{
  precipDepth = 0;
  frostDepth = 0;
  oldabs = abs;
  Tw = airTemp;
```

```
}

precipDepth += precip;//incriments total precipitation depth
if ( precipDepth > 0.0011 ) // derived experimentally
{
  precipDepth = 0.0011;
}
if (Tw <= 273.16 && bridgeTemp <= 273.16 ) // snow on bridge.
{
  // only 0.025 in water (~.25 in. of snow) allowed because of plowing
  //Snow density assumed 1/10 of water.
  if ( precipDepth > 0.00063 )
  {
    precipDepth = 0.00063;
  }
}
if ( precipDepth == 0 )
{
  Tw = airTemp;
}

//this is the equilibrium temperature between precip accumulation and the bridge
Te = ( Cw * (Mw * Tw + Mf*airTemp) + Cc * Mc * bridgeTemp ) /
(Cw * (Mw + Mf) + Cc * Mc );
if ( precipDepth > 0 )
```

```
{
   totalDepth = precipDepth + frostDepth / 10.0;
   frostDepth = 0;
}

//phase change stuff
if ( Tw > 273.16 && bridgeTemp > 273.16 ) // just evaporation or condensation
{
   evapRate = evaporation ( hm, M, R, bridgeTemp, Patm, airTemp);
   condition = 0;//dry
   if(totalDepth > 0.0)
   {
      condition = 5;//wet
   }
}

if ( Tw >= 273.16 && bridgeTemp <= 273.16 ) // freezing/condensation/evaporation
{
   Tw = bridgeTemp = Te;
   if ( Te >= 273.16 ) // no freezing - evaporation or condensation
   {
      evapRate = evaporation ( hm, M, R, bridgeTemp, Patm, airTemp);
      condition = 5;//wet
   }
   else // freezing
```

```
{
  heatFlux = kbridge * ( 273.16 - Te ) / (thickness);//q' = k dT/dx
  freezeRate = heatFlux / Lf;//the amount that will freeze with the amount
  // of excess energy available between the equilibrium temperature and 273.16
  if (freezeRate/waterDensity * 60 <= (totalDepth - frozen))
  {
    frozen = freezeRate/waterDensity * 60 + frozen;
    condition = 4; //freezing
  }
  else// if possible freezing exceeds whats available to freeze (all frozen)
  {
    heatFlux = (totalDepth - frozen) / 60.0 * waterDensity;
    frozen = totalDepth;
    condition = 2;//icy/snowy
  }
  Tw = 273.16;
  if ( frozen > precipDepth )//takes care of straggling precip
  {
    condition = 2;//icy/snowy
    if (frostDepth > 0.0 )
    {
      condition = 1;//frosty
    }
    Tw = Te;
    frozen = totalDepth;
```

```
            heatFlux = 0;
        }
    }
}

else if ( Tw <= 273.16 && bridgeTemp <= 273.16 )
// snow/frost. sublimation, no melting
{
    // frost accumulation/evaporation possible
    // this version does allow frost formation over existing precipitation accumulation, but
    // it will not be labeled as "frost," just additional accumulation of snow/ice.
    evapRate = evaporation ( hm, M, R, bridgeTemp, Patm, airTemp);
    if ( precipDepth ==0 )
    {
        //frost will form if evapRate is negative – water flux toward the bridge surface
        // depth after a minute of accumulation/evap. Density is a tenth of water.
        frostDepth += ( -600 * evapRate / waterDensity );
        condition = 1;//frosty
        if (frostDepth <= 0 )
        {
            frostDepth =0.0;
            heatFlux = 0.0;
            condition = 0; //dry
        }
        totalDepth = frostDepth / 10.0;//total depth is in liquid equivalent
```

```
    Tw = bridgeTemp;
  }

  // only 0.025 in water (~.25 in. of snow) allowed because of plowing
  //Snow density assumed 1/10 of water.
  //cout<<Tw<<" "<<bridgeTemp<<" "<<Te<<endl;
  Tw = bridgeTemp = Te;
  if (precipDepth >0 && frostDepth == 0)
  {
    condition = 2;//icy/snowy
    //frost will form over snow if evapRate is negative - flux toward the bridge surface
  }
  //reduces the sw absorptivity when frost, ice, or snow is present
  if (totalDepth > 0.0)
  {
    abs = oldabs * (1-(700.0*totalDepth));
  }
}

else if ( Tw <= 273.16 && bridgeTemp > 273.16 ) // melting possible
{
  Tw = bridgeTemp = Te;
  if ( Te <= 273.16 ) // no melting
  {
    heatFlux = 0;
```

```
    condition = 2;//snowy/icy
    if (frostDepth > 0.0 )
    {
        condition = 1;//frosty
    }
}
else // melting - heat taken from bridge
{
    heatFlux = kbridge * ( 273.16 - Te ) / (thickness);//q' = k dT/dx
    freezeRate = heatFlux / Lf;//the amount that will melt with the amount
    // of excess energy available between the equilibrium temperature and 273.16
    if (freezeRate/waterDensity * 60 <= frozen)
    {
        frozen = freezeRate/waterDensity * 60 + frozen;
        condition = 3;//melting
    }
    else// if possible melting exceeds whats available to melt
    {
        heatFlux = frozen / 60.0 * waterDensity;
        frozen = 0;
        condition = 5;//wet
    }
    frostDepth = freezeRate/waterDensity * 60 + frostDepth;
    Tw = 273.16;
    if ( frozen < 0 || frostDepth <0)// just in case frostDepth or frozen goes -
```

```
        {
            Tw = Te;
            bridgeTemp = Te;
            frostDepth =0;
            heatFlux = 0;
            frozen = 0;
            condition = 5; //wet
        }
        Tw = 273.16;
    }
}

// if statements make sure evaporation rate does not exceed totalDepth,
//the amount on the bridge
//decreases or increases the total depth based on evaporation rate.
// doesn't alter melting or freezing values
if (condition != 3 && condition != 4)
{
    if ( totalDepth > (evapRate * 60 / waterDensity) )
    {
        totalDepth = totalDepth - (evapRate * 60 / waterDensity);
        precipDepth = precipDepth - (evapRate * 60 / waterDensity);
        if(frostDepth > 0.0)
        {
            precipDepth = 0.0;
```

```
    }
    heatFlux = -1 * evapRate * Lv;
    if (condition == 2 || condition == 1)
    {
      heatFlux = -1 * evapRate * (Lv + Lf);
    }
  }
  else // when evapRate exceeds total depth
  {
    heatFlux = -1 * totalDepth * waterDensity * Lv / 60.0;
    if (condition == 2 || condition == 1)
    {
      heatFlux = -1 * totalDepth * waterDensity * (Lv + Lf) / 60.0;
    }
    totalDepth = 0;
    precipDepth = 0;
    Mw = 0;
    condition = 0;//dry
  }
}

//corrects if totalDepth or precipDepth go negative for some reason
if ( totalDepth < 0 || precipDepth < 0 || frostDepth < 0)
{
  heatFlux = 0.0;
```

```
    totalDepth = 0;
    precipDepth = 0;
    condition = 0;//dry
    frostDepth = 0.0;
  }

  return heatFlux;
}

float evaporation (float hm, float M, float R, float bridgeTemp, float Patm, float airTemp)
{
  //this is a function to calculate the evaporation rate over water or ice, depending on
  // bridge temperature.

  static float Psat;// pressure of water vapor at saturation
  static float evapRate;//evaporation rate kg/s/m2

  if (bridgeTemp > 273.16)
  {
   Psat = 6.112 * exp( 17.67 * ( bridgeTemp - 273.16)/( bridgeTemp - 29.5))/1000.0;//bars
  }
  else
  {
    Psat = 6.1115* exp(( 23.036 - ( bridgeTemp - 273.16) /333.7) *
    ( bridgeTemp - 273.16) / (6.82 + bridgeTemp))/1000.0;//bars
```

```
    //this is over ice. this is different from saturation over water! Buck, JAM 1981
  }
  evapRate = hm * M / R * ( Psat / bridgeTemp - Patm / airTemp);
  // kg/sec per unit area
  return evapRate;
}

float radiative(float SW, float LW, float tempSfc, float absorptivitySW,
float absorptivityLW, float airtemp)
{
  // This function is used to find the radiative energy flux available
  // to influence the bridge temperature

  static const float stephanBoltz = 5.67 * pow(10,-8); //(W m-2 K-4)
  float radiation; //energy flux ( W m-2) received from atmosphere
  // incoming radiation minus emitted radiation
  radiation = ( absorptivityLW * LW ) + ( absorptivitySW * SW ) -
  absorptivityLW * stephanBoltz * pow(tempSfc,4.0) ;
  return radiation;
}

float convection( float wind, float Ta, float Ts )
{ /* this function finds the right convection heat transfer coefficient (in Wm-2)
  given windspeed and the temperature difference between the air and bridge
  surface. It will be the average coefficient over a 10 meter span of bridge.
```

```
h is computed for "tripped" flow, where turbulence begins at the very edge
of the bridge. Immediately turbulent flow is a good assumption because of
bridge rails and other bridge complexities.*/

float h, reynoldsNumber;//, Cf, xCrit;
static const float kair = 2.4 * pow(10,-2);// conductivity of air Wm-1k-1
static const float length = 10 ; //meters. length of bridge exposed to air flow
static const float prandtlNumber = 0.71;// for air
static const float kinematicViscosity = 1.4 * pow(10,-5) ;//m2 s-1 for air
static const float g = 9.8;// ms-2 gravity
static float Gr; // Grashof # ratio of bouyancy to viscous forces
static float Ra; // Rayleigh # = Gr*Pr
static float Nuf; //Nusselt# for forced conv.
//Nu=hL/k = Dimensionless temp gradient at the surface.
static float Nun; //Nusselt # for natural conv
static float Nu; // total Nusselt number = Nuf+-Nun.
//Stability suppresses total conv, Instability inhances it.

if (wind <= 0)
{
  wind =0.01; // keeps the reynolds number from going to zero.
}

//forced convection...
reynoldsNumber = wind * length / kinematicViscosity;
```

```
Nuf = 0.037*1.5*pow(reynoldsNumber,(0.8)) * pow(prandtlNumber,(1/3.0));

// now for natural conv...
Gr = g * (2/(Ta+Ts))*(Ts-Ta)*pow(length,3)/pow(kinematicViscosity,2);
Ra = prandtlNumber*Gr;
if((Ts-Ta)>=0)
{
  Nun = 0.15* pow(Ra,0.3333);
  Nu = pow((pow(Nuf,3.0) + pow(Nun,3.0)),0.333);
}
else
{
  Ra = Ra *(-1.0);
  Nun = 0.27*pow(Ra,0.25);
  if ((pow(Nuf,3.0) - pow(Nun,3.0))<=0.0)
  {
    Nu = 1.0;
  }
  else
  {
    Nu = pow((pow(Nuf,3.0) - pow(Nun,3.0)),0.333);
  }
}
h = kair * Nu / length;
return h;
```

```
}

float bridgelevels (float radiation, float latentHeat, float tempSfc,
float tempAir, float h, float thickness,
float kbridge, double thermalDiffusivity,int l, int t)
{ /* n is used for node definition, it gives the vertical position of the node.
  At n = 0, is a node representing the top surface of the bridge. Since the
  bridge is much longer and wider than deep, a temperature gradient is
  assumed to exist only in the verical. Max n = 19, total depth is determined
  by the property file. The second array dimension is t, the time in minutes.
  The temperature of any node at any time is stored in the two dimensional array,
  temperature. Nodes are initialized with the temperatures found in"initialize".
  */

  static float length = thickness / 19.0;// m distance between nodes
  //heat transfer rate coefficient, timestep =60 s
  static float M = ((length * length) / (thermalDiffusivity * 60.0));
  float N ;
  N = (1+(h*length/kbridge)) / M ;
  float dummy[6] = {0};// useless floats to pass to function "initialize"
  static float temperature[20][3000];

  if ( N > 0.5 )
  {
    //WARNING: thickness, h, and thermal diffusivity combination creates
```

```
    //numerical instability. Should be less than 0.5. This usually doesn't
    //cause noticable effects. setting N to the largest stable number
    N = 0.499;
}
if ( t > 3000 )
{
    cerr << " file will be shortened to 3000 minutes " << endl;
    exit( 31 );
}
// sets initial bridge node temperatures
if ( l == 0 )
{
    int i = 0;
    temperature[0][t] = tempSfc;
    for ( int c = 1; c < 20; c++)
    {
        temperature[c][t] = initialize( dummy[0], dummy[1], dummy[2], dummy[3],
        dummy[4], dummy[5], (c-1), i );
        if ( temperature[c][t] == 0 )
        {
            cerr<< " intialization = 0. insufficient rwis initialization" << endl;
            exit(20);
        }
    }
}
```

```
// for any other time, t
// for top level, there is conduction, convection, and residual
//(radiative, and latent heat) processes at work
else
{
  temperature[0][t-1] = tempSfc;//makes sure that the surface temperature
  //from the latentHeat function is used
  temperature[0][t] = (2 / M) * ( h * length / kbridge * tempAir + (
  (radiation + latentHeat) * length / kbridge ) +
  temperature[1][t-1]) + ( 1 - (2 * N)) * temperature[0][t-1];

  // for lower levels: just conduction for middle layers,
  // convection for the lowest level.
  for (int n = 1; n < 19; n++ )
  {
    temperature[n][t] = ( 1 / M * (temperature[n-1][t-1] + temperature[n+1][t-1] )
    + (1 - 2 /M ) * temperature[n][t-1]);
  }
  temperature[19][t] = (2 / M) * (h * length / kbridge * tempAir +
  temperature[18][t-1]) + (1 - (2 * N)) * temperature[19][t-1];

  if ( t > 0 && fabs(temperature[0][t-1] - temperature[0][t]) > 8 )
  {
    cerr << " heating/cooling rate too high. check inputs "<<
```

```
        temperature[0][t-1] <<" "<<temperature[0][t] << " "<<t<<endl;
        exit(25);
      }
    }
    if ( temperature[0][t] < 200 )
    {
      cerr<< "bad calculated surface temperature: check inputs "
      <<temperature[0][t]<<" time: "<<t<<endl;
      exit(10);
    }
    return temperature[0][t];
}
```

APPENDIX C. Flowchart of major BridgeT operations

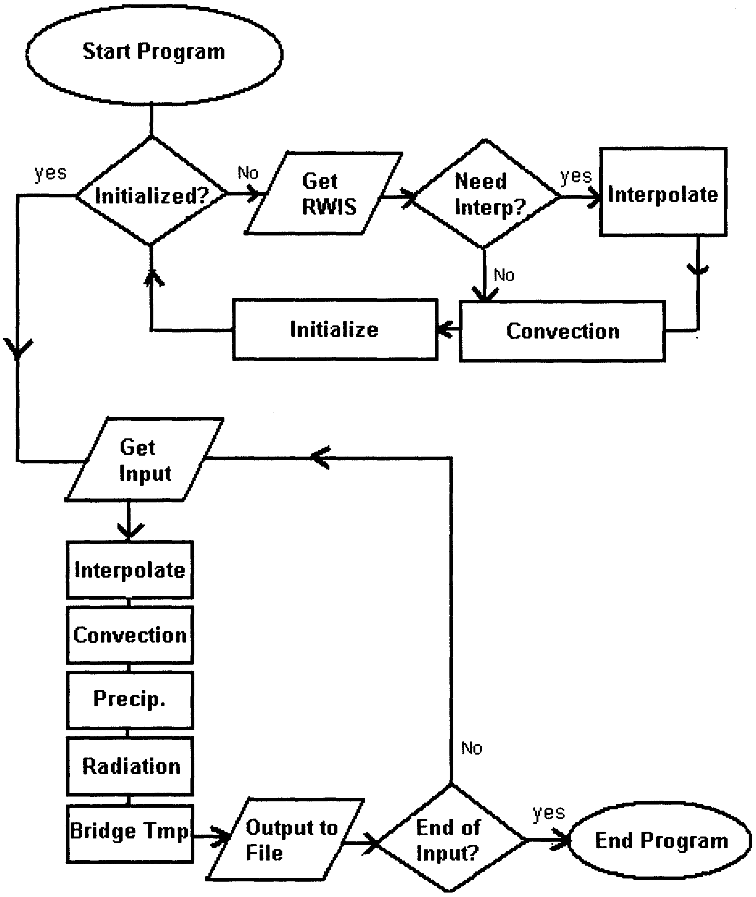

Figure C.1 Flowchart of major BridgeT operations

APPENDIX D. List of physical assumptions used in BridgeT parameterizations

Convection

1. The air encountering the bridge is approximately vertically uniform before reaching the bridge.
2. Due to the small scale of the bridge boundary layer, air is assumed to be incompressible, and density gradients are due to temperature gradients.
3. It was assumed that the velocity of the fluid along the bridge is much greater than velocities in other directions, and that the change in velocity with height above the bridge is greater than changes along the bridge surface.
4. The thermal gradient normal to the bridge surface is much greater than the thermal gradient parallel to the surface.
5. Heat generation due to viscous dissipation can be ignored.
6. Convection is steady-state.

Precipitation

1. Precipitation and bridge surface temperature of the surface node reaches equilibrium during one timestep.

2. Precipitation is assumed to be liquid if the air temperature is at or above 273 K; frozen if the air temperature is below 273 K.

3. Frost cannot form if precipitation accumulation is present on the bridge.

Initialization and bridge temperature prediction

1. Top surface node receives energy fluxes from convection, conduction, longwave and solar radiation, and latent heating.

2. Interior nodes receive energy fluxes from conduction. The bottom surface node receives convection and conduction.

3. The surface nodes represent half of the volume of the interior nodes.

4. Bridge properties (e.g., conductivity, mass, absorptivity) are constant.

APPENDIX E. Bridge frost observation results

Results of frost observations. The "Bridge" column denotes the location of the frost observation. The bridges are located on State Avenue (State), South Dakota Avenue (SD), County Line (CL), and X Avenue (X). The "Frost?" column is marked with a question mark (?) if the observer could not accurately identify bridge frost condition.

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
11/30/01	State	4:56	31.6			No
12/02/01	State	5:05	28.6	9:09	33.5	Yes
12/03/01	State	5:01	23			No
12/06/01	State	4:59	24.8	8:52	22.3	Yes
12/07/01	State	5:01	26.6			No
12/14/01	State	5:00	16.5			No
12/17/01	State	5:08	20			No
12/18/01	State	5:01	28			No
12/27/01	State	5:13	9			No
12/28/01	State	4:57	12			No
12/29/01	State	5:09		10:10	28.4	Yes
12/30/01	State	4:57	-8	9:55	2	Yes
12/31/01	State	5:02	-5			No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
01/03/02	State	5:04	-1.5	8:00		Yes
01/04/02	State	5:00	22			No
01/05/02	State	4:51	26			No
01/06/02	State	4:51	37			No
01/07/02	State	5:06	11	8:02		Yes
01/08/02	State	5:04	24			No
01/11/02	State	5:05	18			No
01/12/02	State	5:03	26	7:00		Yes
01/13/02	State	5:08	33			No
01/15/02	State	5:02	28			No
01/20/02	State	5:00	19.1			No
01/21/02	State	5:03	24.2			No
01/22/02	State	5:02	24			No
01/24/02	State	5:13	12.5	7:11		Yes
01/25/02	State	5:04	24			No
01/28/02	State	5:04	27.5			No
02/02/02	State	8:00				Yes
02/03/02	State	5:00	14.5	9:56	21	Yes
02/04/02	State	5:08	-6			No
02/05/02	State	5:10	4.5			Yes
02/07/02	State	4:10	17	5:12	15	Yes
02/11/02	State	5:13				No
02/13/02	State	5:00	14.5	8:53	16	Yes

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
02/17/02	State	5:07	19	8:00	18	Yes
02/21/02	State	4:56	24			No
02/22/02	State	4:50	20.6			No
03/04/02	State	5:03	-9			No
03/05/02	State	5:05	13			No
03/06/02	State	5:15	25			No
03/12/02	State	4:55	18.2			No
03/13/02	State	5:00	37.3			No
03/15/02	State	5:50	27			No
03/18/02	State	4:46	20			No
03/21/02	State	5:00	-16			No
11/12/02	State	7:55				Yes
11/15/02	State	4:59	23			No
	CL	5:12	18			No
11/16/02	State	5:08	24			No
	CL	5:18	23			No
11/17/02	State	5:03	11			No
	CL	5:15	11	5:51	11	No
11/18/02	State	5:05	22			No
	CL	5:14	23			No
11/19/02	State	4:52				No
	CL	5:02				No
11/20/02	State	5:15				No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	CL	5:25				No
11/21/02	State	4:58				No
	SD	5:04				No
	CL	5:14				No
11/22/02	State	5:17	18	5:50		No
	CL	5:30	13			No
11/23/02	State	6:26	26	6:54		No
	SD	6:35	24	6:47		No
	CL	6:39	25	8:45	25	Yes
11/24/02	State	5:10	38			No
	CL	5:15	31			No
11/25/02	State	5:20	8			No
	CL	5:38	0			No
11/26/02	State	5:15	12			No
	CL	5:29	12			No
11/27/02	State	5:20	8			No
	CL	5:32	4			No
11/28/02	State	5:08	9			No
	CL	5:20	6			No
11/29/02	State	5:04	26			No
	CL	5:17	27			No
12/01/02	State	4:52				No
	SD	4:59				No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	CL	5:05				No
12/02/02	State	4:51				No
	SD	4:55				No
	CL	5:02				No
12/03/02	State	4:51				No
	SD	4:57				No
	CL	5:02				No
12/04/02	State	5:15	4			No
	CL	5:25	8			No
12/05/02	State	5:05				No
12/06/02	State	5:09	4	9:33		Yes
	SD					Yes
	CL	5:20	4	9:42	9	Yes
12/07/02	State	5:17	18.5			No
	CL	5:36	13			No
12/08/02	State	5:23	4.5			No
	CL	5:31	9			No
12/09/02	State	5:16	-13.5	6:27	-6	No
12/10/02	State	5:55	13			No
	SD	6:00				No
	CL	6:17	14			No
12/11/02	State	5:14	33			No
	SD					No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	CL	5:24	33	9:15	31.5	Yes
12/12/02	State	4:58	32			?
	SD	5:07	33			?
	CL	5:16	33			?
12/14/02	State	5:20	21.5			No
	SD					No
	CL	5:30	19			No
12/15/02	State	5:02	27			No
	SD					No
	CL	5:12	27			No
12/16/02	State	4:54	26			No
	SD	5:06				No
	CL	5:09	29			No
12/17/02	State	4:58	29			No
	SD	5:06				No
	CL	5:12	32			No
12/19/02	State	5:17	18	8:13		Yes
	SD	5:40		8:02		Yes
	CL	5:29	17	7:50	21	No
12/20/02	State	4:50	29			No
	SD	5:00				No
	CL	5:07	30			No
12/21/02	State	5:02	26			No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	SD	5:12				No
	CL	5:17	24			No
12/22/02	State	5:12	11			No
	SD	5:33				No
	CL	5:23	13			No
12/23/02	State	5:08	12			No
	SD					No
	CL	5:17	12			No
12/24/02	State	4:54	15			No
	SD					No
	CL	5:03	12			No
12/26/02	State	4:58	8	9:49		Yes
	SD			8:39		Yes
	CL	5:09	10	9:56	15	Yes
12/27/02	State	5:01	25	10:50		Yes
	SD					Yes
	CL	5:11	22	10:55	28	Yes
12/28/02	State	4:48	18			No
	SD	4:57				No
	CL	5:03	19			No
12/29/02	State	4:54	26			No
	SD	5:04				No
	CL	5:10	30			?

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
12/30/02	State	4:58	30			No
	SD	5:07				No
	CL	5:15	30			No
12/31/02	State	4:53	15			No
	SD	5:02				No
	CL	5:08	14			No
01/01/03	State	5:10	23			No
	SD					No
	CL	5:20	23			No
01/02/03	State	4:58	20			No
	SD					No
	CL	5:07	19			No
01/03/03	State	4:55	13			No
	SD					No
	CL	5:05	11			No
01/04/03	State	4:51	23			No
	SD	5:00				No
	CL	5:07	24			No
01/05/03	State	4:57	36			No
	SD	5:09				No
	CL	5:18	30			No
01/06/03	State	5:03	30			No
	SD					No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	CL	5:12	28			No
01/07/03	State	4:53	19	9:35	25	Yes
	SD			9:40		Yes
	CL	5:03	19.5	9:43	22	Yes
01/08/03	State	4:53	27			No
	SD	5:02				No
	CL	5:08	30			No
01/09/03	State	4:54	30			No
	SD	5:02				No
	CL	5:08	28			No
01/10/03	State	5:10	16			No
	SD	5:18				No
	CL	5:27	14			No
01/11/03	State	5:05	4.5			No
	SD					No
	CL	5:14	2			No
01/12/03	State	4:56	4			No
	SD					No
	CL	5:06	5			No
01/13/03	State	5:20	9.5			No
	SD	5:25				No
	CL	5:30	7			No
01/14/03	State	4:57	13			No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	SD	5:05				No
	CL	5:10	12			No
01/15/03	State	5:16	6.3			No
	SD	5:19				No
	CL	5:31	6			No
01/19/03	State	5:33	12.9	7:54	10.7	?
	SD	5:52		8:05		?
	CL	5:47	13.8			No
01/20/03	State	5:22	23.6	6:07	24.1	?
	SD	5:42				?
	CL	5:36	20.2			No
01/21/03	State	4:51	13			No
	SD	5:01				No
	CL	5:08	13			No
01/23/03	State	5:01	-10			No
	SD					No
	CL	5:11	-9			No
01/24/03	State	5:16	13.6			No
	SD	5:12				No
	CL	5:30	12			No
01/25/03	State	4:52	16			No
	SD	5:03				No
	CL	5:10	14			No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
01/28/03	State	4:55	28			?
	SD	5:04				No
	CL	5:10	31			No
01/30/03	State	4:56	25			No
	SD	5:05				No
	CL	5:13	26			No
02/01/03	State	5:07	28.5			?
	SD					?
	CL	5:20	28			No
02/02/03	State	4:59	34			?
	SD					No
	CL	5:11	34			No
02/06/03	State	4:53	17			No
	SD	5:01				?
	CL	5:08	17			?
02/07/03	State	5:14	6.1			No
	SD	5:18				No
	CL	5:26	6.8			?
02/08/03	State	4:52	25			No
	SD	5:01				No
	CL	5:07	25			?
02/11/03	State	4:47	17			No
	SD	4:56				No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	CL	5:03	16			No
02/12/03	State	5:06	7.1			No
	SD					No
	CL	5:16	7			No
02/13/03	State	4:45	24			No
	SD	4:54				No
	CL	5:02	24			No
02/14/03	State	5:05	30			?
	SD					No
	CL	5:16	30			No
02/17/03	State	5:12	11.5			?
	SD					?
	CL	5:23	9.5			No
02/18/03	State	4:53	25.5	9:10	40	Yes
	SD					Yes
	CL	5:04	24	9:30	29.9	Yes
02/19/03	State	4:57	27			No
	SD	5:04				No
	CL	5:12	25			No
02/20/03	State	4:46	34			?
	SD	4:55				?
	CL	5:02	33			No
02/21/03	State	4:46	35			No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	SD	4:57				No
	CL	5:05	33			No
02/25/03	State	5:07	4			?
	SD	5:19				No
	CL	5:25	5			?
02/26/03	State	4:56	12			No
	SD	5:05				No
	CL	5:11	12	9:15	24	Yes
02/27/03	State	4:59	24			No
	SD	5:08				No
	CL	5:14	25			No
02/28/03	State	4:53	27.5			?
	SD					?
	CL	5:03	26.5			No
03/07/03	State	4:49	31.5			?
	SD					No
	CL	5:01	29			No
03/08/03	State	4:55	22.5			?
	SD					?
	CL	5:08	23.5			No
03/09/03	State	5:02	9			No
	SD					No
	CL	5:11	8			No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
03/11/03	State	5:01	24			No
	SD	5:10				No
	CL	5:17	23			No
03/12/03	State	4:55	36			No
	SD	5:06				No
	CL	5:14	36			No
03/13/03	State	4:51	39			No
	SD	5:03				No
	CL	5:12	37			No
03/14/03	State	4:46	40			No
	SD	4:54				?
	CL	5:00	37			No
03/15/03	State	4:52	39			No
	SD					No
	CL	5:01				No
03/21/03	State	5:00	31.7	6:36	34	?
	SD					?
	CL	5:11	31.4	6:44	33.6	?
11/19/03	State	5:00	37			No
	SD	5:10				No
	CL	5:30	36.5			No
	X	5:25	36.5			No
11/21/03	State	4:58	34.4			No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	SD					No
	CL					No
	X					No
11/25/03	State	5:28	25.3			No
	SD	5:32				No
	CL	5:38	26.1			No
	X	5:45	29.8			No
11/26/03	State	5:20	29			No
	SD	5:30				No
	CL	5:40	29			No
	X	5:50	28.5			No
11/27/03	State	5:15	29	6:30	28	No
	SD	5:25				No
	CL	5:30	28.5	6:05		No
	X	5:40	28.5	6:15	28	No
11/29/03	State	5:10	19			No
	SD	5:15				No
	CL	5:20	20			No
	X	5:30	20			No
11/30/03	State	4:55	33			No
	SD	5:05				No
	CL	5:10	33.5			No
	X	5:20	33			No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
12/01/03	State	5:00	32			No
	SD	5:10				No
	CL	5:15	33			No
	X	5:25	32			No
12/02/03	State	5:26	40.9			No
	SD	5:31				No
	CL	5:36	37.6			No
	X	5:42	37			No
12/06/03	State	4:55	30			No
	SD					No
	CL		31			No
	X					No
12/07/03	State	5:01	29	10:08	39.8	Yes
	SD	5:08		10:16		Yes
	CL	5:17	28	10:25	38.2	Yes
	X	5:27	27.5	8:25		Yes
12/08/03	State	5:05	39			No
	SD	5:12				No
	CL	5:19	36.5			No
12/09/03	State	5:20				No
	SD					No
	CL					No
	X					No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
12/12/03	State	5:15	17	6:30	20	No
	SD	5:20		6:40		No
	CL	5:30	18	6:50	21	No
	X	5:40	18.5	7:00	21	No
12/13/03	State	5:20	14			?
	SD	5:29				?
	CL	5:32				No
	X	5:38	15.1			?
12/14/03	State	5:05	28.8			?
	SD	5:12				?
	CL					No
	X					No
12/15/03	State	5:05	32.2			No
	SD	5:12				No
	CL					No
	X					No
12/17/03	State	5:33	20	9:44		Yes
	SD	5:38		9:46		?
	CL	5:44	19.5	9:48	18.5	Yes
	X	5:51	18	9:04		?
12/18/03	State	5:05	29	8:10	28	Yes
	SD	5:10		6:30		No
	CL	5:20	28	6:40	28	No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	X	5:30	30	7:05	33	Yes
12/19/03	State	5:00	26	7:15	27	No
	SD	5:05		7:20		No
	CL	5:15	26	7:30	26	No
	X	5:25	25	7:40	27	No
12/20/03	State	5:05	19	6:30	20	No
	SD	5:15		6:40		No
	CL	5:20	18	6:50	19	No
	X	5:30	19	7:00	19	No
12/21/03	State	5:05	31.5	6:55	31.5	No
	SD	5:10		7:00		No
	CL	5:15	32	6:30	31.5	No
	X	5:25	31	6:40	31	No
12/22/03	State	4:49				No
	SD	4:52				No
	CL	5:01				No
	X	5:07				No
12/24/03	State	5:20	16	9:42	23	Yes
	SD	5:25		9:45		?
	CL	5:32	14.8	9:53	22	Yes
	X	5:41	15	8:55		?
12/25/03	State	5:51	20			No
	SD	6:08				No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	CL	5:58	18			No
	X		19.3			No
12/26/03	State	8:30				No
12/29/03	State	5:20	30.7			No
	SD	5:25				No
	CL	5:30	30.6			No
	X	5:38				No
01/08/04	State	5:00	20.5	7:00	22	No
	SD	5:10		7:10		No
	CL	5:20	20.5	7:20	22	No
	X	5:30	20	7:30	22.5	No
01/09/04	State	5:00	13.5	5:45	13	No
	SD	5:10				No
	CL	5:20				No
	X	5:30	14			No
01/10/04	State	5:20	20			No
	SD	5:26				No
	CL	5:33	19.5			No
	X	5:39	21.5			No
01/11/04	State	5:00	22.5	8:00	25.5	No
	SD	5:10				No
	CL	5:20	23	8:15	25	No
	X	5:30	22	8:25	26	No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
01/12/04	State					No
	SD					No
	CL					No
	X					No
01/13/04	State	5:00	27.5	6:20	26	No
	SD	5:10				No
	CL	5:20	26.5	5:55	26	No
	X	5:30	27	6:05	27	No
01/15/04	State	5:12	20			No
	SD	5:17				No
	CL	5:22	19.1			No
	X		18.3			No
01/18/04	State	5:14	6.5			No
	SD	5:21				No
	CL	5:27	8.5			No
	X	5:32	7			No
01/19/04	State	5:15	5	7:15	7	No
	SD	5:25		7:20		No
	CL	5:35	3	7:30	7	No
	X	5:45	4	7:40	7	No
01/20/04	State	5:10	11	7:10	13	No
	SD	5:15		7:20		No
	CL	5:25	11	7:25	12	No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	X	5:35	11	7:40	12	No
01/21/04	State	5:15	20	7:15	24	No
	SD	5:20		7:20		No
	CL	5:30	21	7:30	23	No
	X	5:40	22	7:40	24	No
01/22/04	State	5:13	3			No
	SD	5:21				No
	CL	5:25	6			No
	X	5:31				No
01/24/04	State	5:10	23			No
	SD	5:15				No
	CL	5:20	23.1			No
	X	5:26				No
01/26/04	State	5:00	14	6:30	13	No
	CL	5:20	15	6:45	12	No
	X	5:25	14	6:55	13	No
01/27/04	State	4:55	-4	7:10	-6	No
	CL	5:15	-2	7:30	-4	No
	X	5:25	-4	7:45	-6	No
01/30/04	State	5:00	-5	7:20	-5	No
	CL	5:25	-3	7:35	-5	No
	X	5:35	-4	7:45	-4	No
01/31/04	State	5:00	-4	6:20	-7	No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	CL	5:20	-2	6:45	-5	No
	X	5:30	-4	6:55	-5	No
02/01/04	State	5:00	12	6:35	13	No
	CL	5:25	10	6:50	12	No
	X	5:35	11	7:00	12	No
02/02/04	State	5:00	10			No
	CL	5:25	11			No
	X	5:40	11			No
02/03/04	State	5:00	6			No
	CL	5:20	7			No
	X	5:35	7			No
02/04/04	State	5:00	3			No
	CL	5:25	5			No
	X	5:35	3			No
02/11/04	State	5:00	15			No
	CL	5:20	16			No
	X	5:35	15			No
02/16/04	State	5:00	5	6:30	4	No
	CL	5:20	4	6:45	4	No
	X	5:30	3	6:55	3	No
02/17/04	State	5:00	7	5:40	6	No
	CL	5:15	8	5:55	8	No
	X	5:25	8	6:10	8	No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
02/18/04	State	5:00	12	5:50	11	No
	CL	5:25	14	6:15	13	No
	X	5:35	13	6:25	13	No
02/20/04	State	5:00	33	5:50	33	No
	CL	5:25	34	6:10	34	No
	X	5:35	34	6:20	33	No
02/22/04	State	5:00	33	6:20	31	No
	CL	5:15	33	6:35	33	No
	X	5:25	32	6:45	32	No
02/23/04	State	5:00	33	6:30	32	No
	CL	5:20	34	6:50	33	No
	X	5:30	33	7:05	31	No
02/24/04	State	5:10	34	6:45	33	No
	CL	5:30	35	7:00	33	No
	X	5:45	33	7:10	32	No
02/25/04	State	5:00	30	6:30	28	No
	CL	5:15	31	6:50	29	No
	X	5:30	30	7:00	28	No
02/26/04	State	5:10	28		32.9	Yes
	SD	5:26				Yes
	CL	5:20	27.1		35.5	Yes
	X					No
02/29/04	State	5:00	36	5:45	35	No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
	CL	5:20	37	6:00	37	No
	X	5:30	35	6:15	36	No
03/01/04	State	5:00	40	5:50	39	No
	CL	5:20	40	6:15	38	No
	X	5:35	39	6:30	38	No
03/02/04	State	5:10	37	6:00	35	No
	CL	5:35	37	6:25	36	No
	X	5:45	37	6:40	34	No
03/03/04	State	5:00	35	5:45	34	No
	CL	5:20	36	6:05	35	No
	X	5:30	34	6:15	34	No
03/05/04	State	5:00	36	5:50	35	No
	CL	5:20	35	6:05	35	No
	X	5:35	34	6:15	33	No
03/08/04	State	5:00	30	6:35	28	No
	CL	5:25	29	6:50	28	No
	X	5:35	30	7:00	29	No
03/09/04	State	5:00	33	6:30	32	No
	CL	5:20	35	6:50	33	No
	X	5:30	32	7:00	32	No
03/10/04	State	5:05	33	6:35	32	No
	CL	5:30	34	6:50	34	No
	X	5:45	33	7:00	32	No

Date	Bridge	First Ob. Time	First Temp.	Last Ob. Time	Last Temp.	Frost?
03/12/04	State	5:00	20	6:30	18	No
	CL	5:15	19	6:50	18	No
	X	5:30	19	7:05	17	No
03/19/04	State	6:00	31.5			No
	SD	6:05				No
	CL	6:10	31.5			No
	X	6:19	32.5			No

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